Neutrino detectors for future facilities - II

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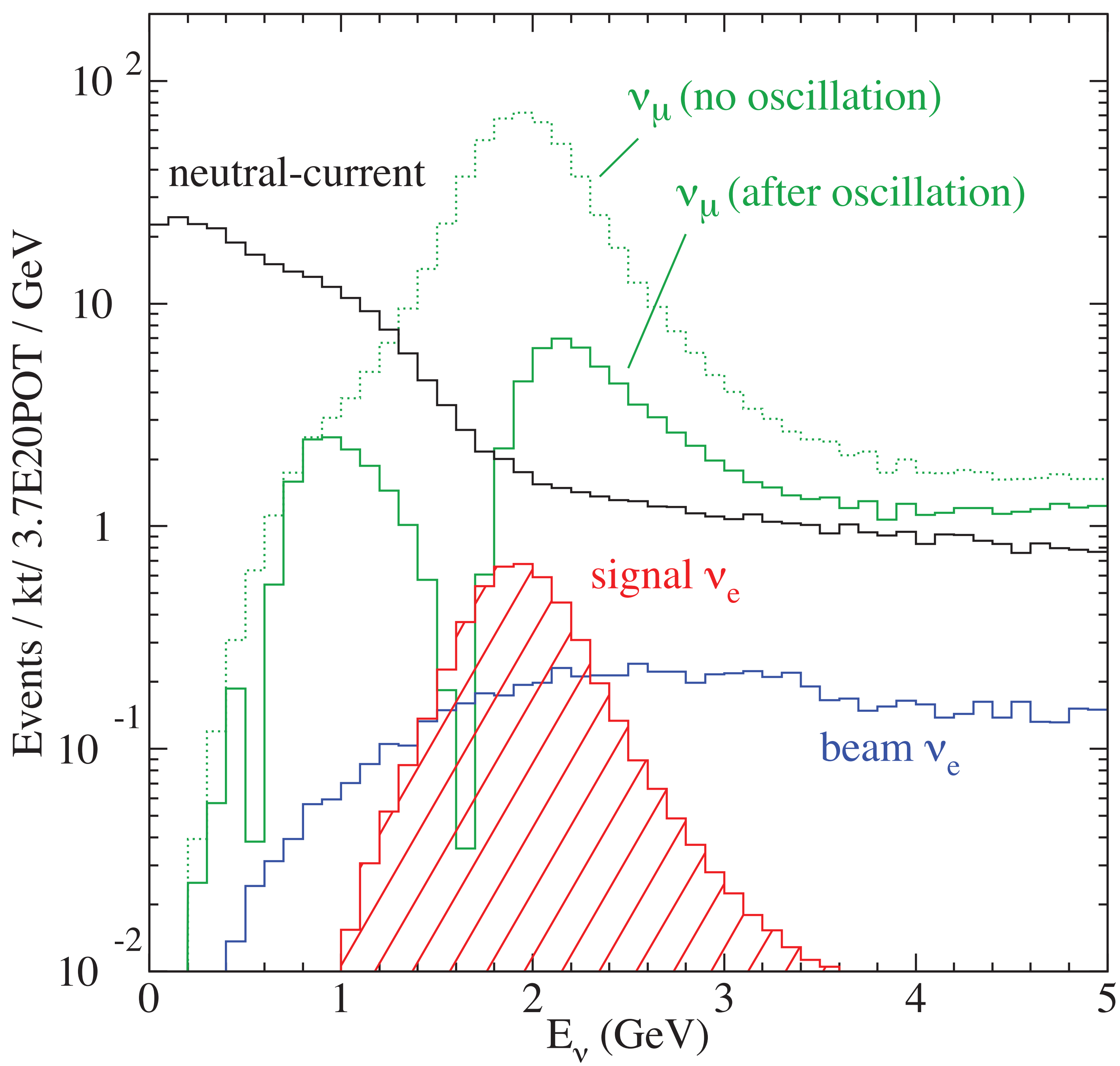
Neutrino detectors optimized for electron reconstruction

$\nu_\mu \rightarrow \nu_e$ and/or $\nu_e \rightarrow \nu_e$

Neutrino detectors optimized for $\nu_x \rightarrow \nu_e$

- I've put three basic detector technologies into this category
  - Water Cherenkov : T2K experiment
  - Totally Active Scintillator Detector ("TASD") : NOvA experiment
  - Liquid Argon Time Projection Chambers : ICARUS and future facilities
- The main focus of these experiments is electron neutrino appearance in muon neutrino beam.
- However, they can, of course, measure muons and in general have good performance for muon detection! I'll comment in the next lecture on questions about measuring the sign of the muons. The experiments listed above do not plan to run these detectors with magnetic fields and hence don't have sensitivity to the *sign* of muons.

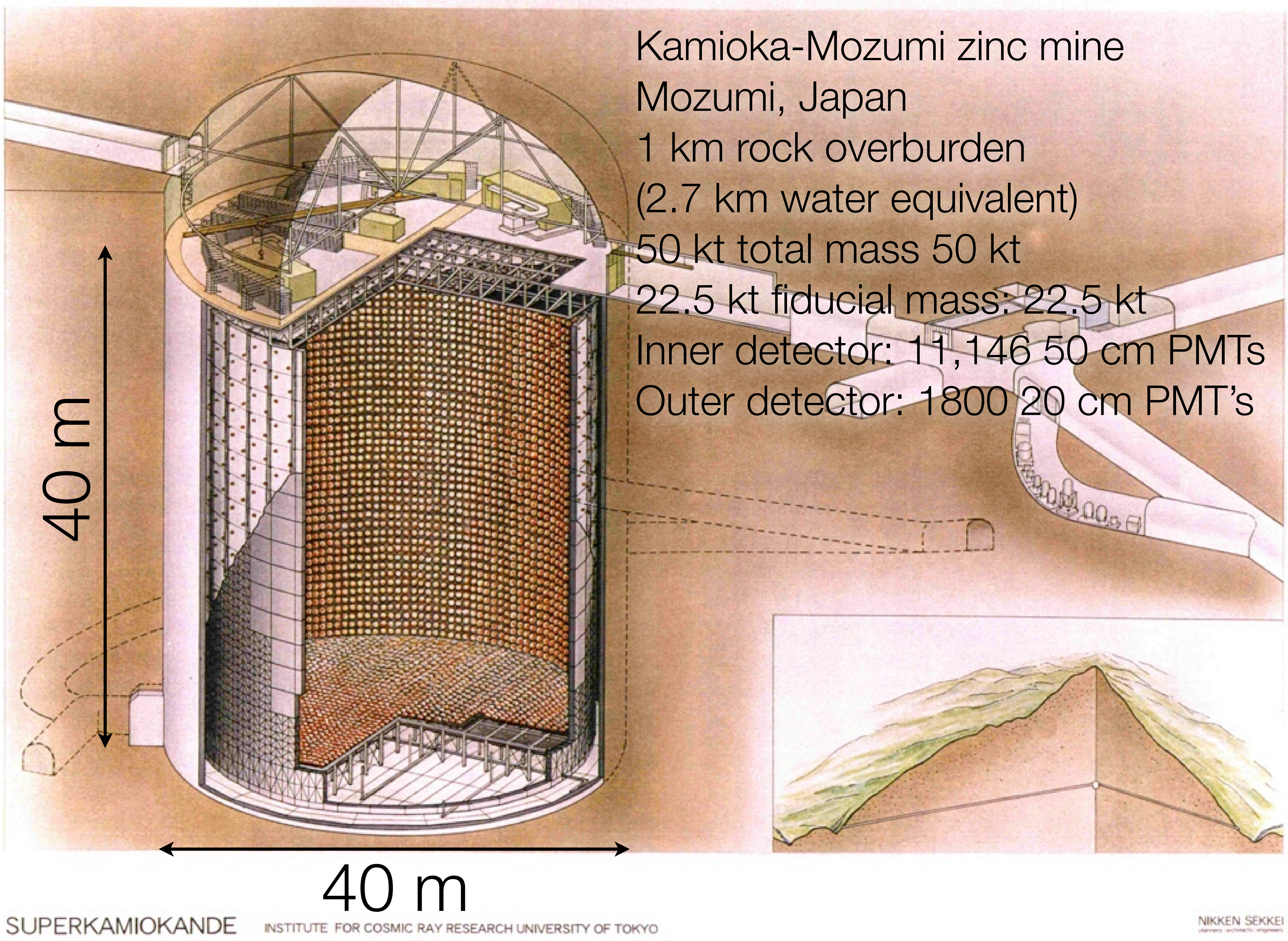
The basic problem for $\nu_\mu \rightarrow \nu_e$ detection at a "Super Beam" facility



- In muon neutrino beams, an electron neutrino signal competes with many backgrounds
- Need large mass to get signal up
- Need fine granularity to distinguish muon neutrino and neutral-current event topologies from electron neutrino event topologies
- Need good energy resolution to home in on signal energy window

Water Cherenkov

Super-Kamiokande



Kamioka-Mozumi zinc mine
Mozumi, Japan
1 km rock overburden
(2.7 km water equivalent)
50 kt total mass 50 kt
22.5 kt fiducial mass: 22.5 kt
Inner detector: 11,146 50 cm PMTs
Outer detector: 1800 20 cm PMT's

Cherenkov effect

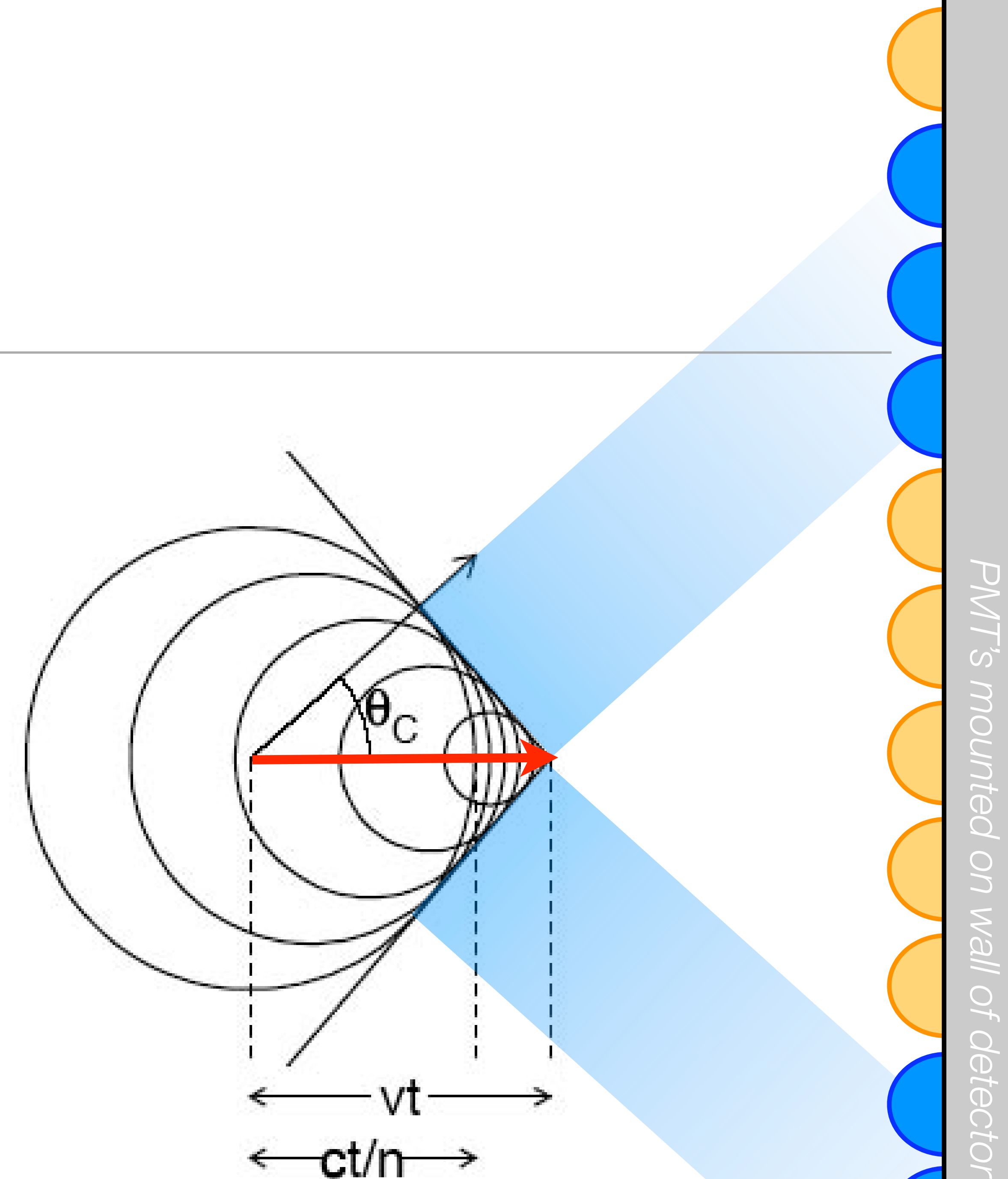
- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction *n*, a “shock wave” of radiation develops at a critical angle:

$$\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$

- Threshold for Cherenkov radiation:

$$K = m\left(\frac{n}{\sqrt{n^2-1}} - 1\right)$$

m	:	particle mass [GeV]
p	:	particle momentum [GeV]
E	:	particle total energy [GeV]
K	:	particle kinetic energy [GeV]
β	:	particle velocity/c
n	:	index of refraction
θ_C	:	Cherenkov angle



For water, n=1.33

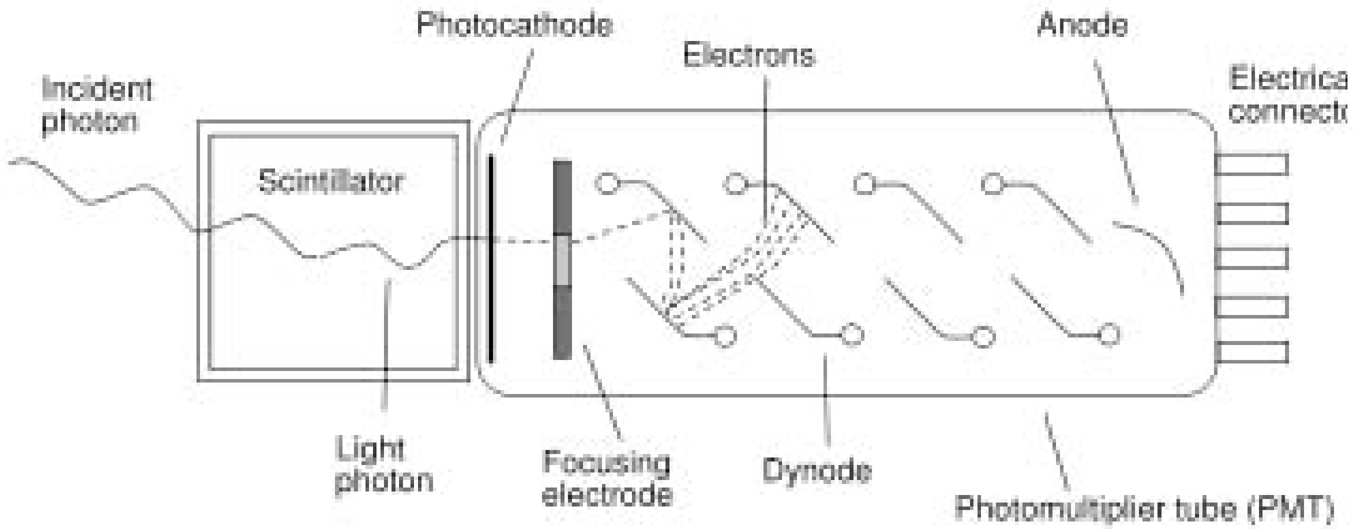
$\theta_C\vert_{\beta=1.0}$	42°
$\theta_C\vert_{\beta=0.9}$	33°

	K_{thresh} [MeV]
e	0.26
μ	55
τ	920
π	72
p	480

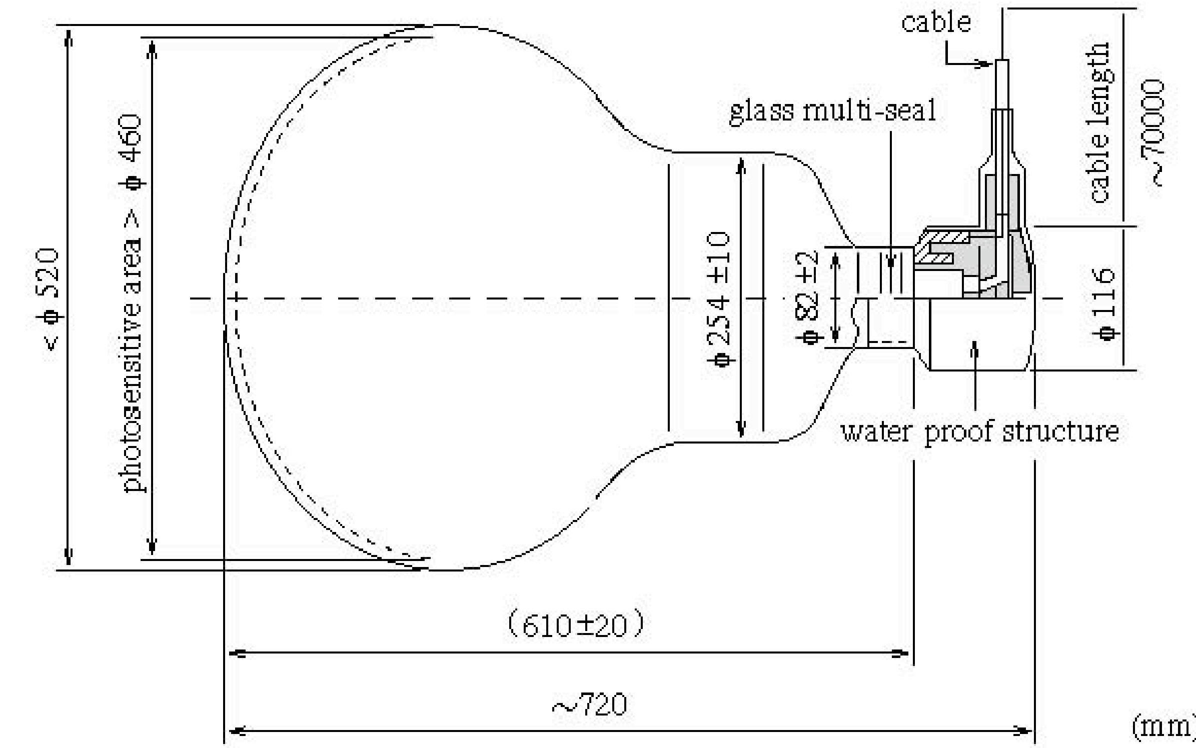
Photomultiplier tubes

Photon incident on the *photocathode* produces a *photo-electron* via the photoelectric effect. Probability to produce a photoelectron is called the *quantum efficiency* of the PMT.

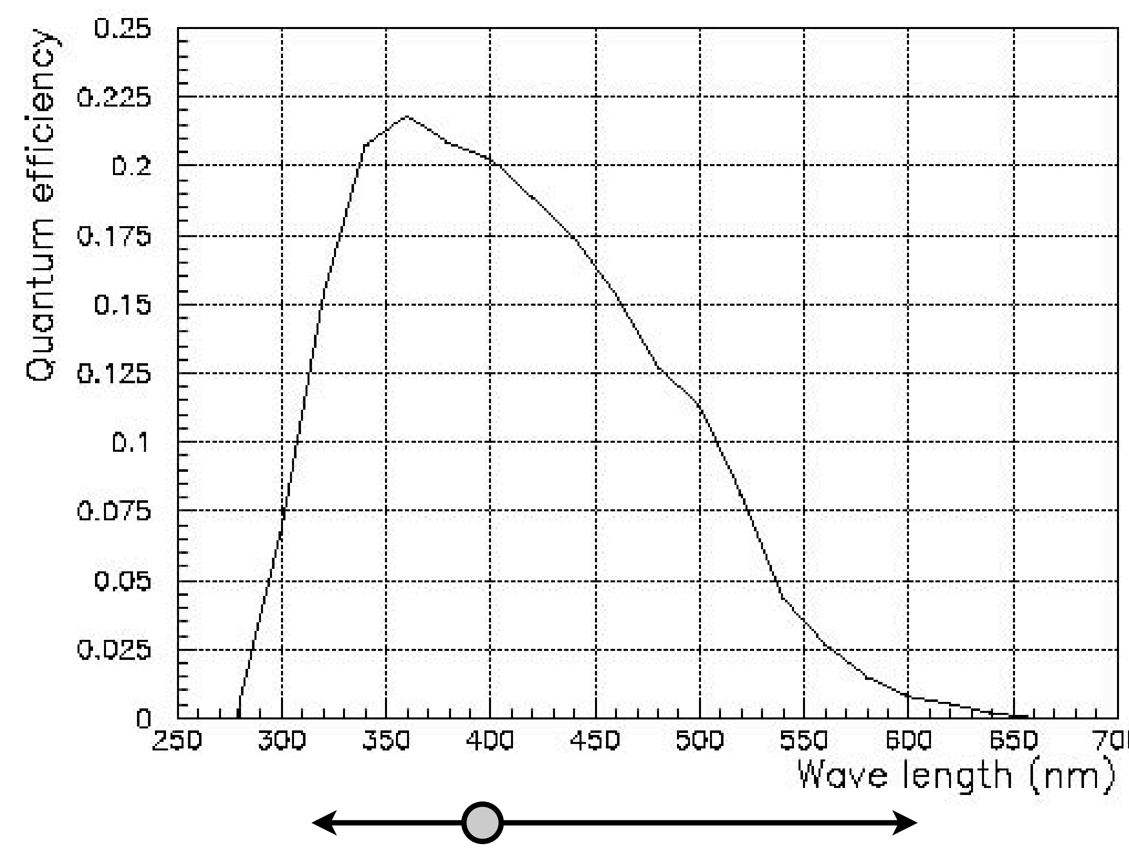
Output signal is seen as a current delivered to the *anode*. Typical *gains* are 10^6 yielding pC-scale currents



A series of plates called *dynodes* are held at high voltage by the *base* such that electrons are accelerated from one dynode to the next. At each stage the number of electrons increases. Probability to get first electron from the photocathode to the first dynode is called the *collection efficiency.*



100 ns transit time, 2.2 ns time resolution



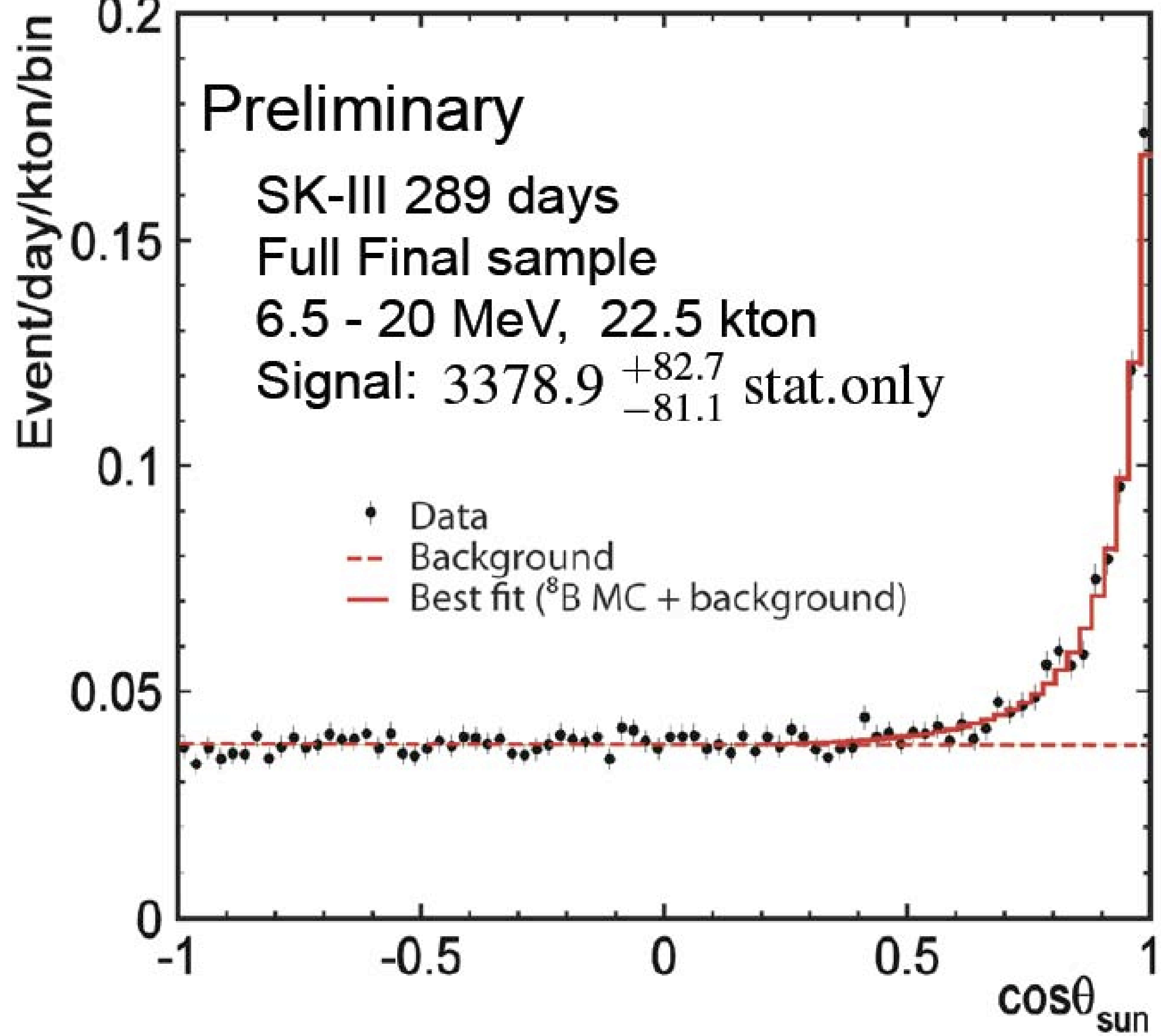
wavelength of Cherenkov photons in water

General performance

- Sensitive to a wide range of energies. Capable of electron and photo detection down to ~5 MeV

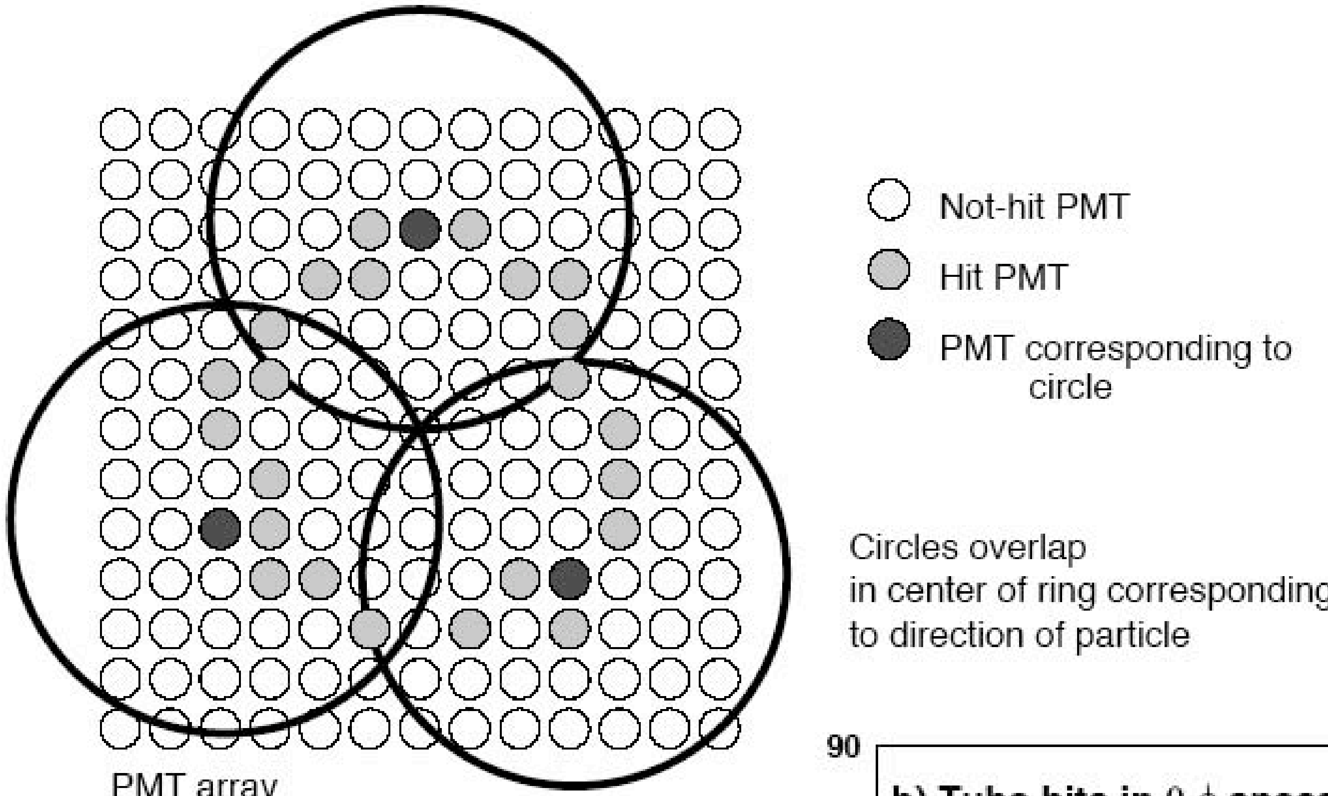
- Tracks produce rings on the walls. In high multiplicity events overlap of rings makes reconstruction difficult. Typically, analyses focus on quasi-elastic events which are very often single-track events.

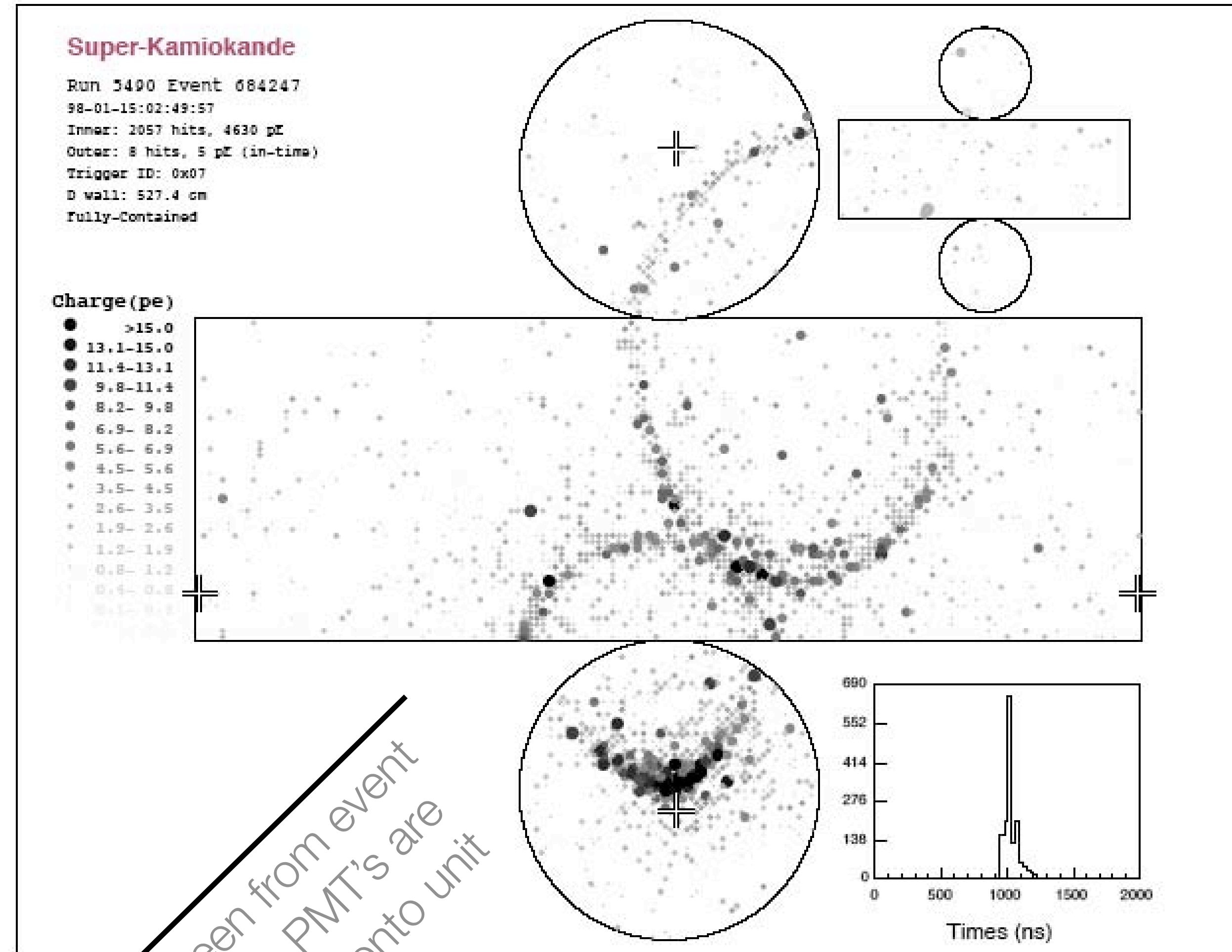
- For single track QE events, neutrino energy reconstructed from kinematics (see next slide)



- Events with pions (and other tracks) that are below Cherenkov threshold lead to backgrounds for the quasi-elastic selection

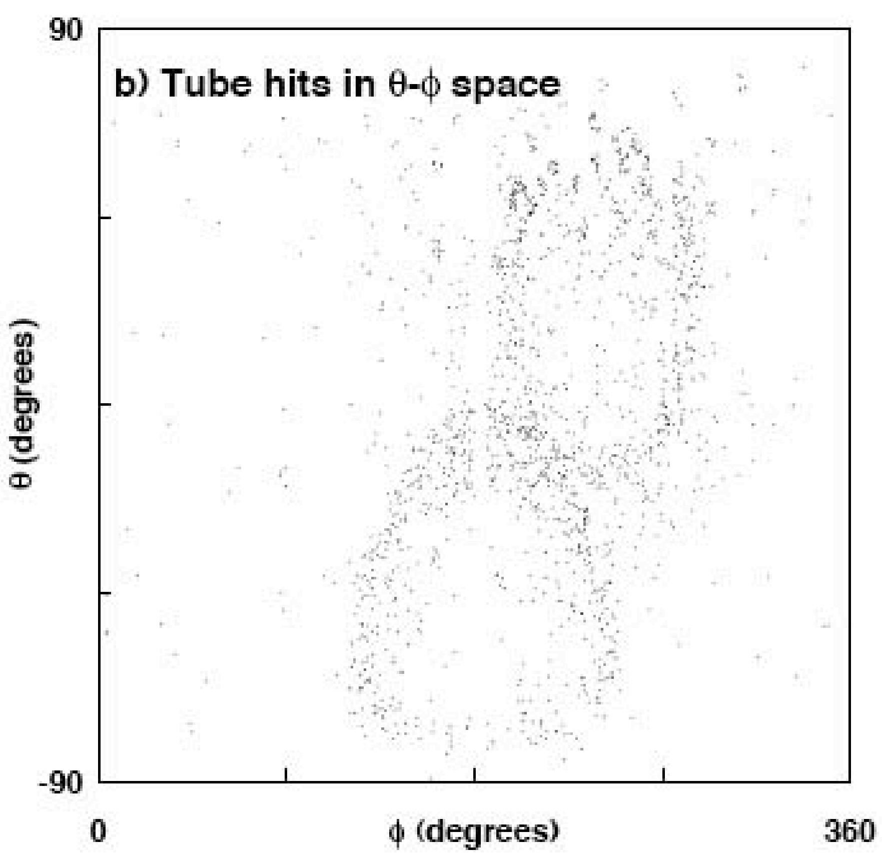
Water Cherenkov: Ring Counting

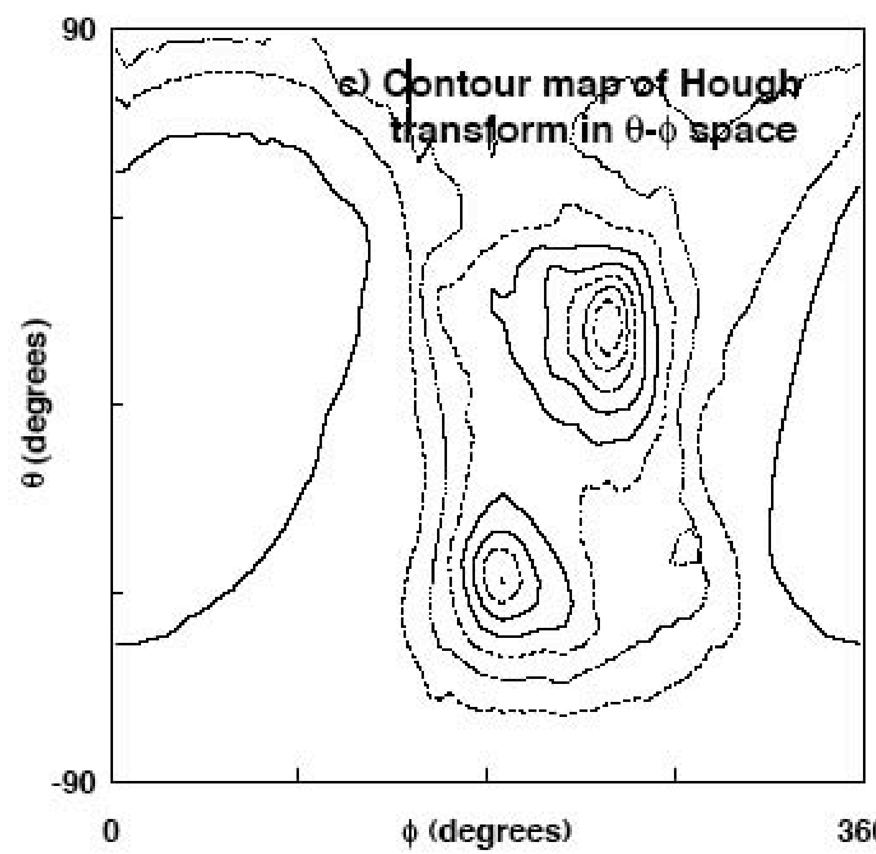




Figures from M. Earl's PhD Thesis

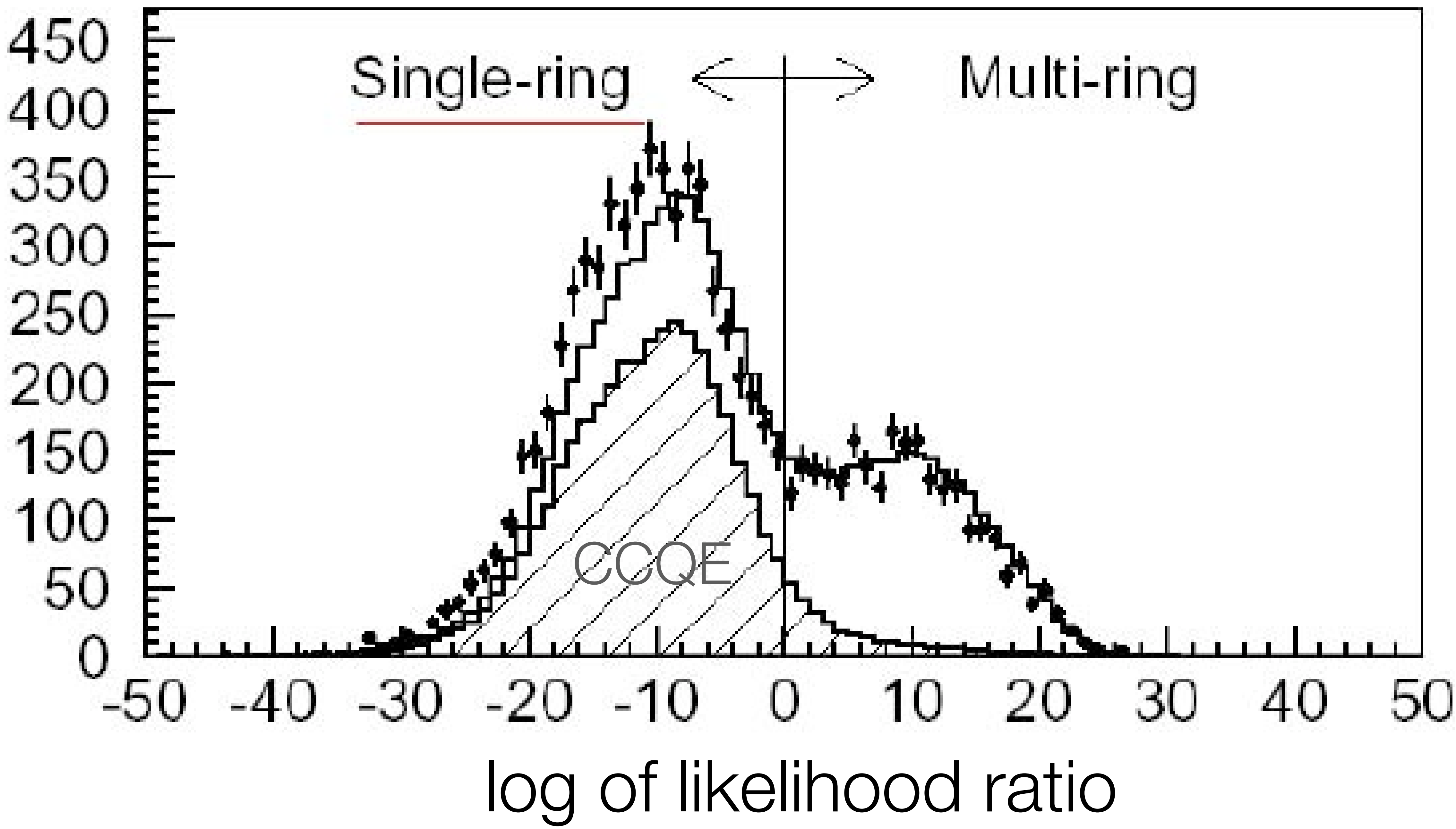
As seen from event vertex, PMT's are mapped onto unit sphere

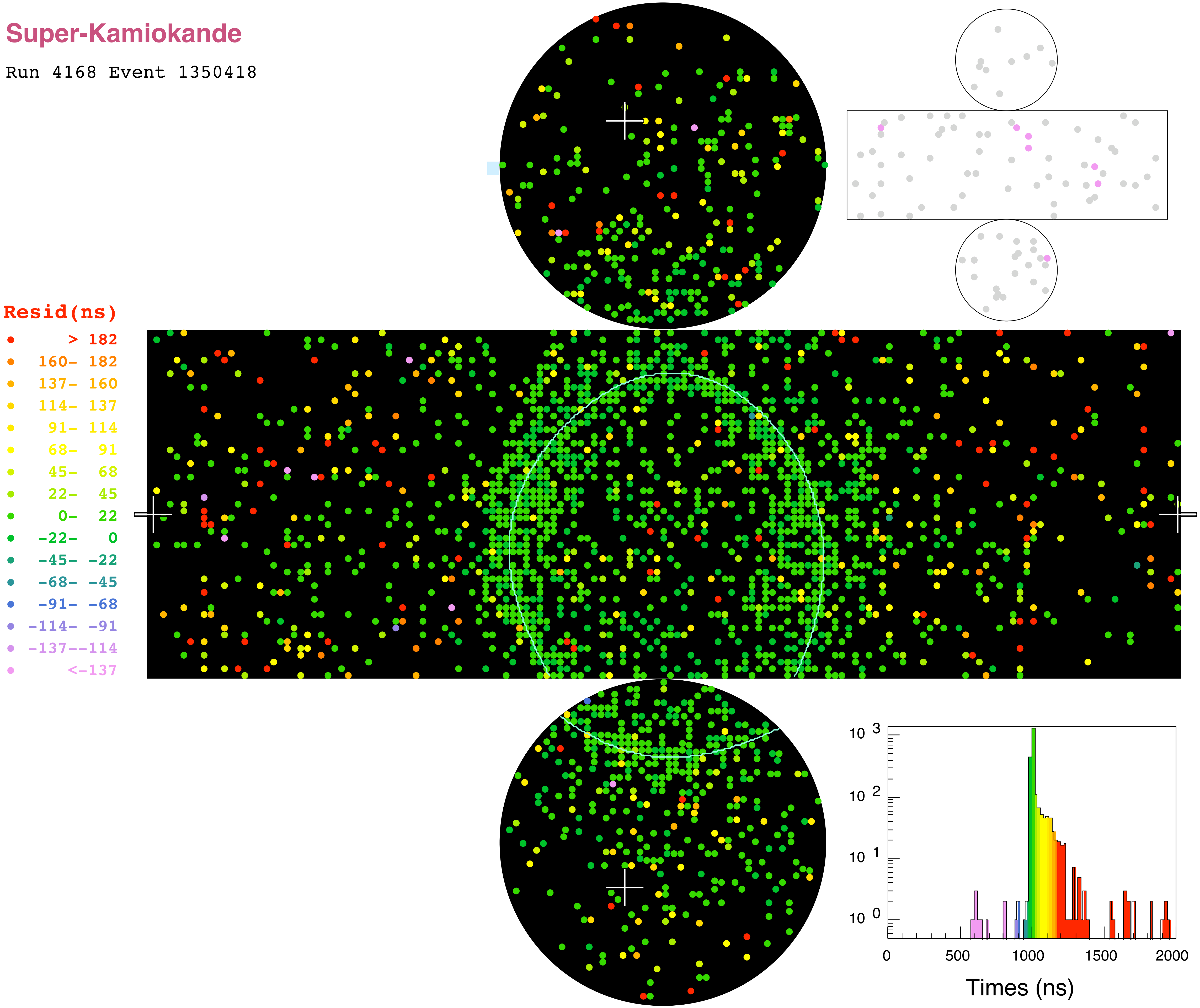




If you know the pattern you are looking for (line, circle, oval, etc.) the Hough transform is method for converting a pattern recognition problem to a peak finding problem

Ring counting likelihood




Super-Kamiokande
Run 4168 Event 1350418
Resid(ns)
> 182
160- 182
137- 160
114- 137
91- 114
68- 91
45- 68
22- 45
0- 22
-22- 0
-45- -22
-68- -45
-91- -68
-114- -91
-137--114
<-137
10 3
10 2
10 1
10 0
0
500
1000
1500
2000
Times (ns)

Quasi-elastic reconstruction

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l cos\theta_l}$$

From 2 body kinematics

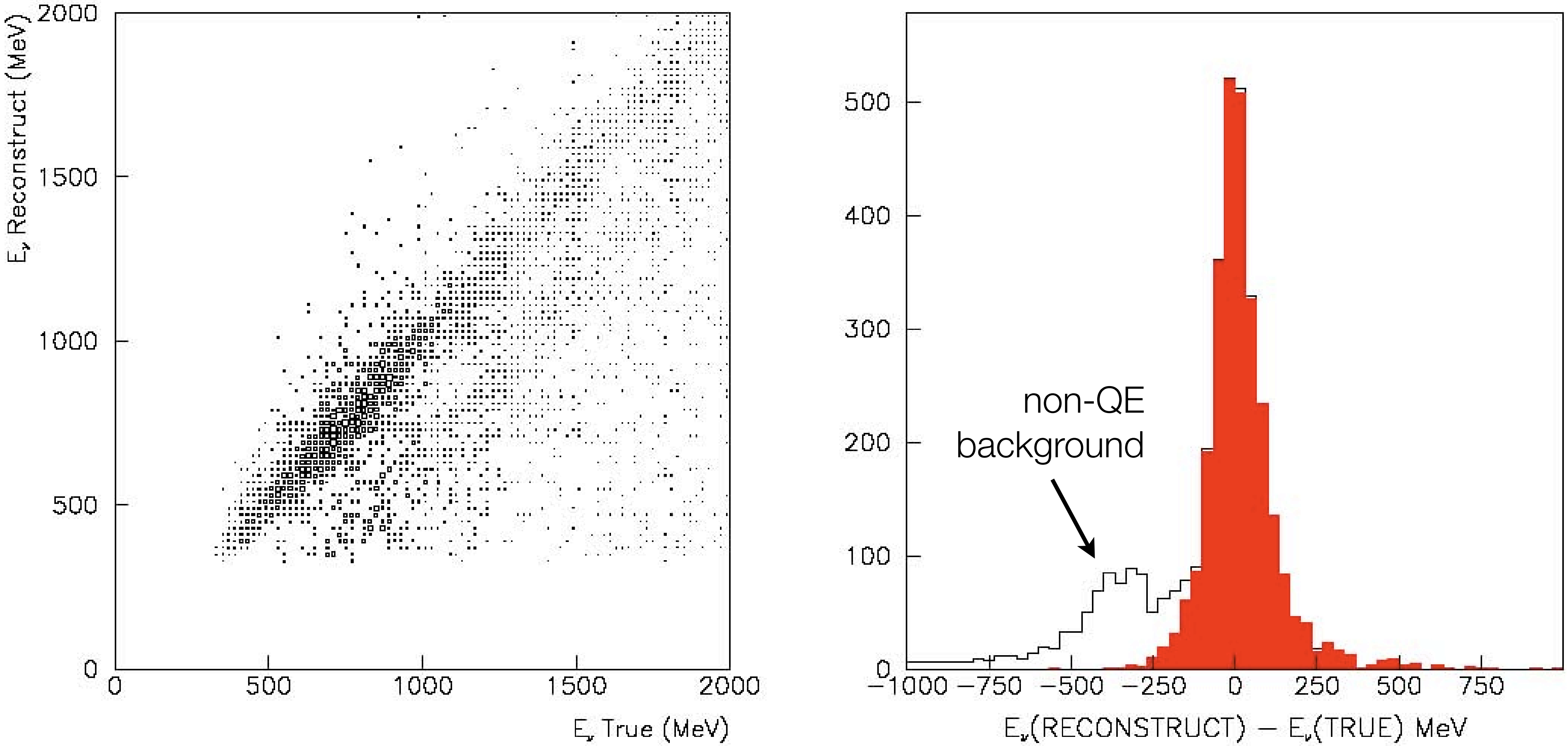
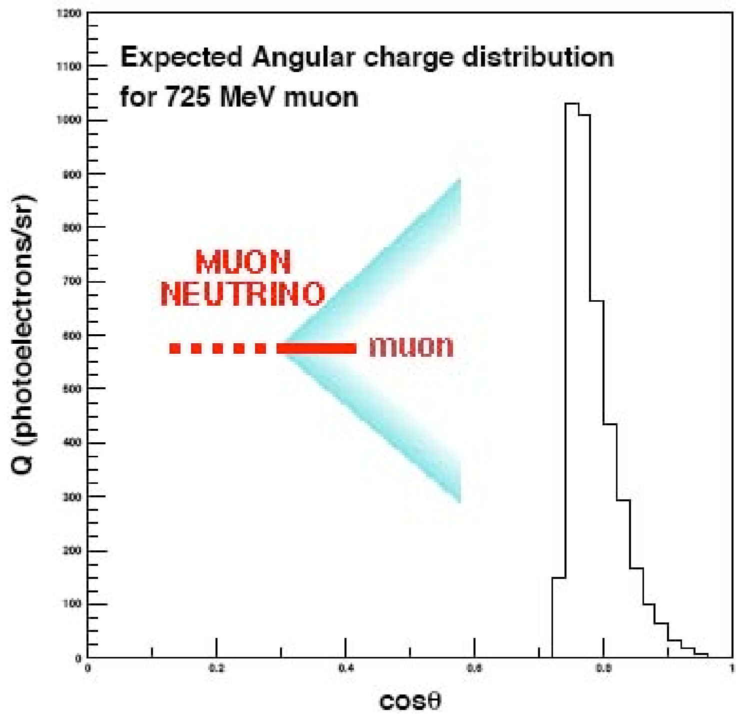


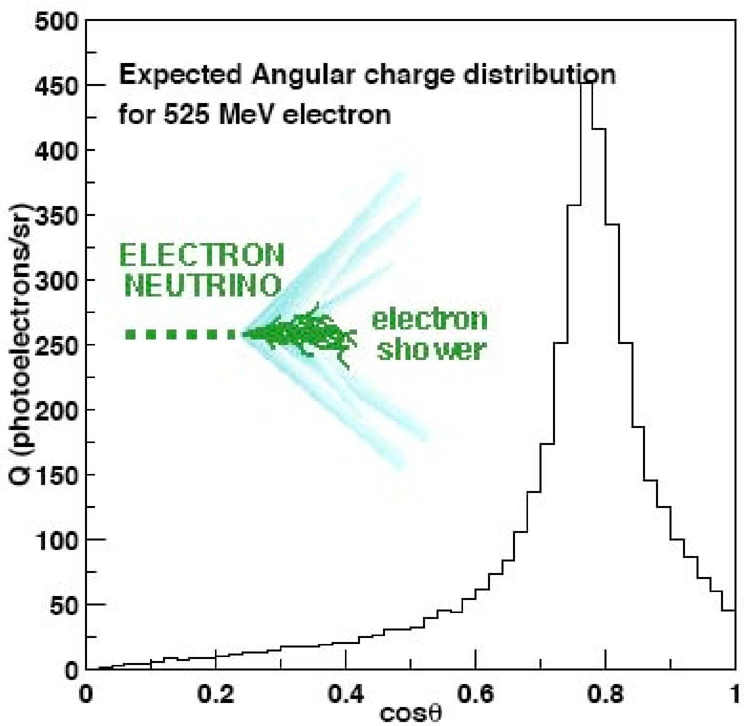
Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for ν_μ events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of ν_μ events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.

Water Cherenkov: e/μ identification

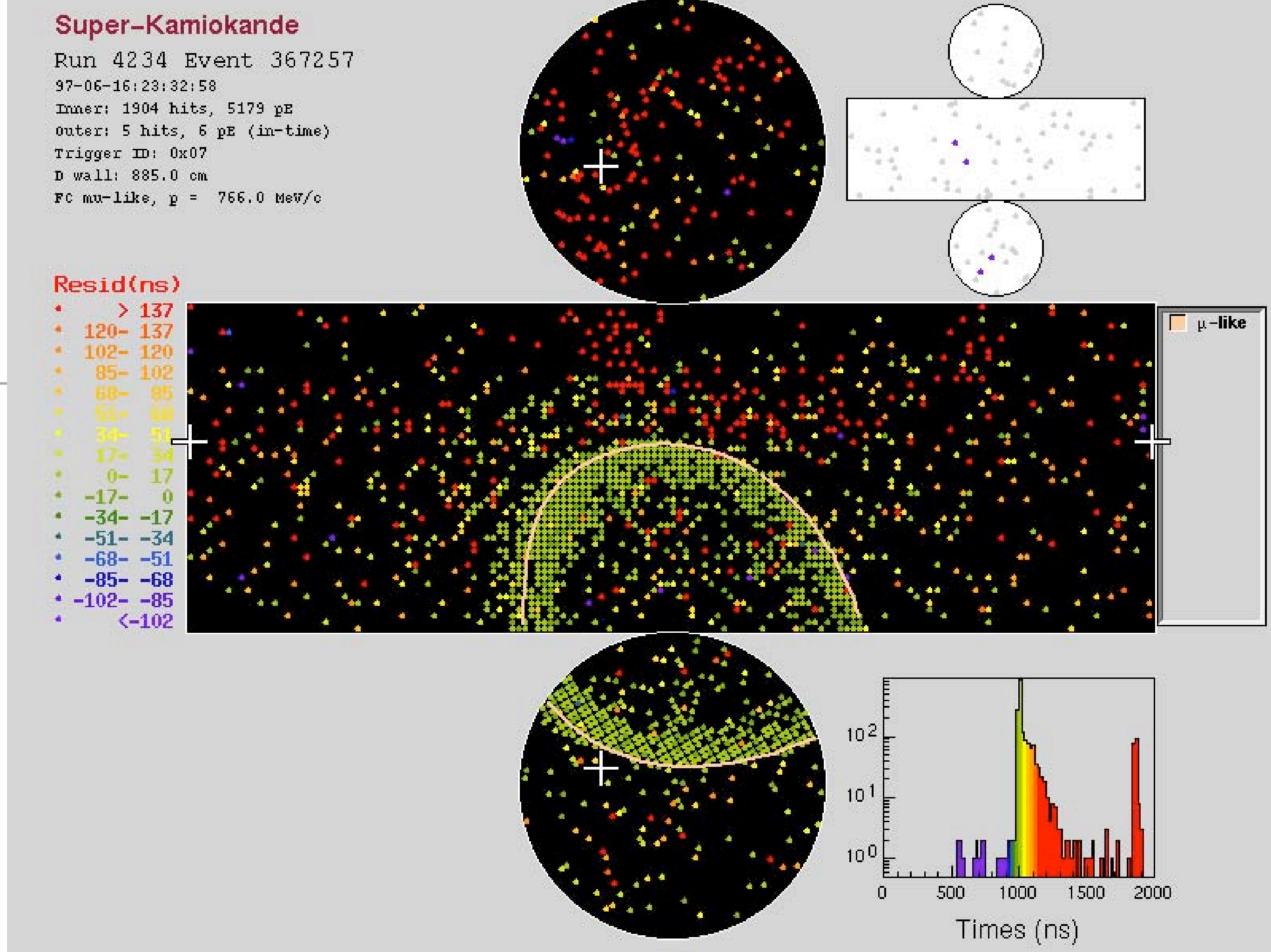
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.

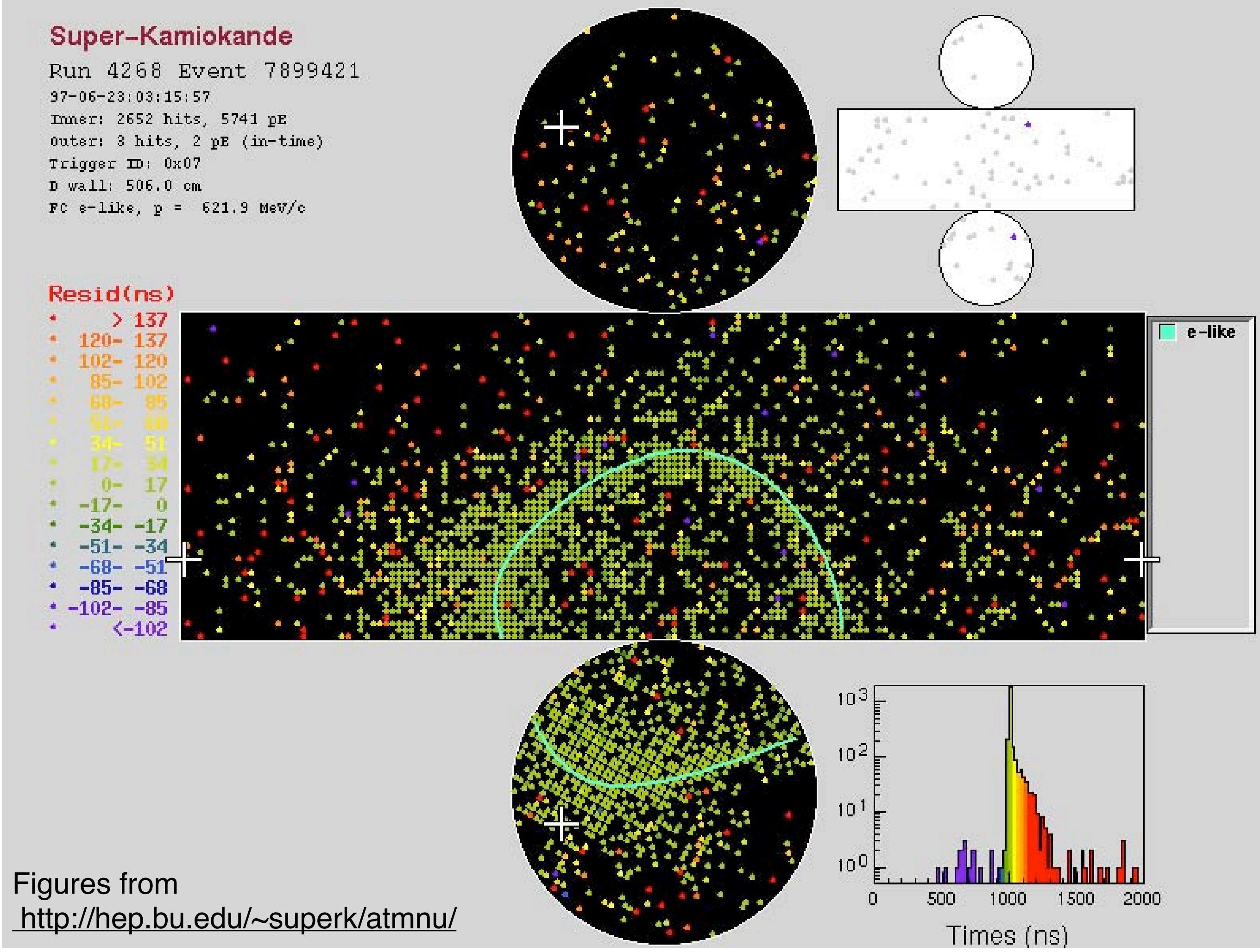


- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.



Figures from M. Earl’s PhD Thesis





Figures from
http://hep.bu.edu/~superk/atmnu/

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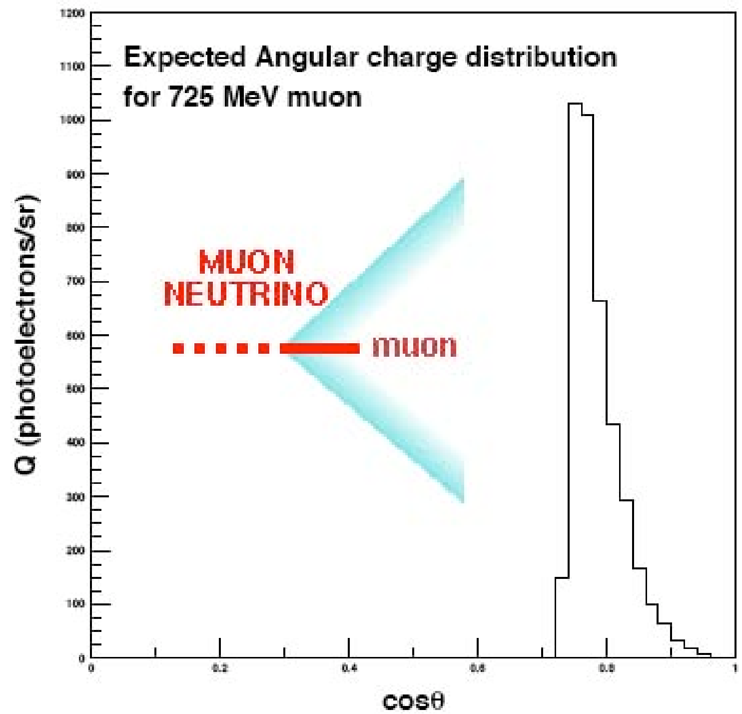

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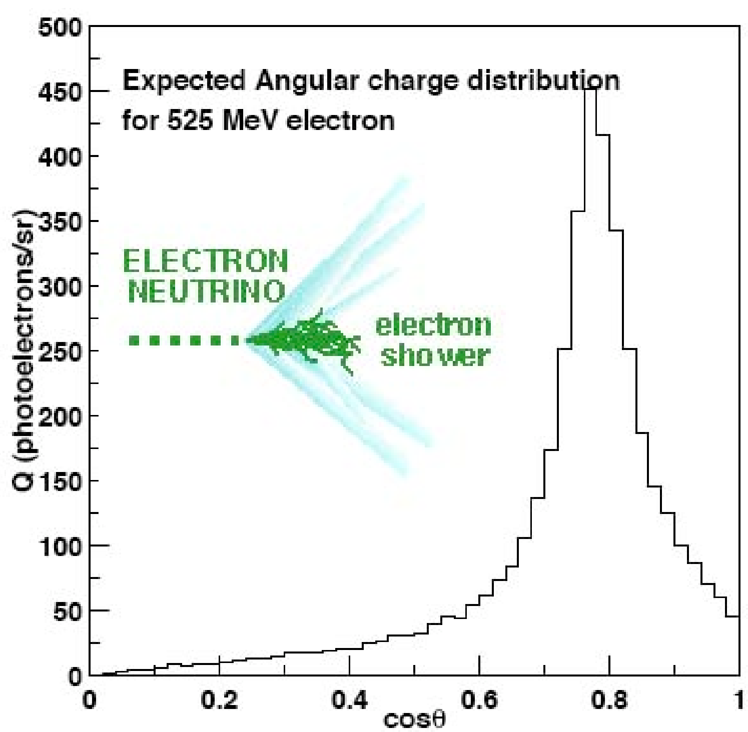

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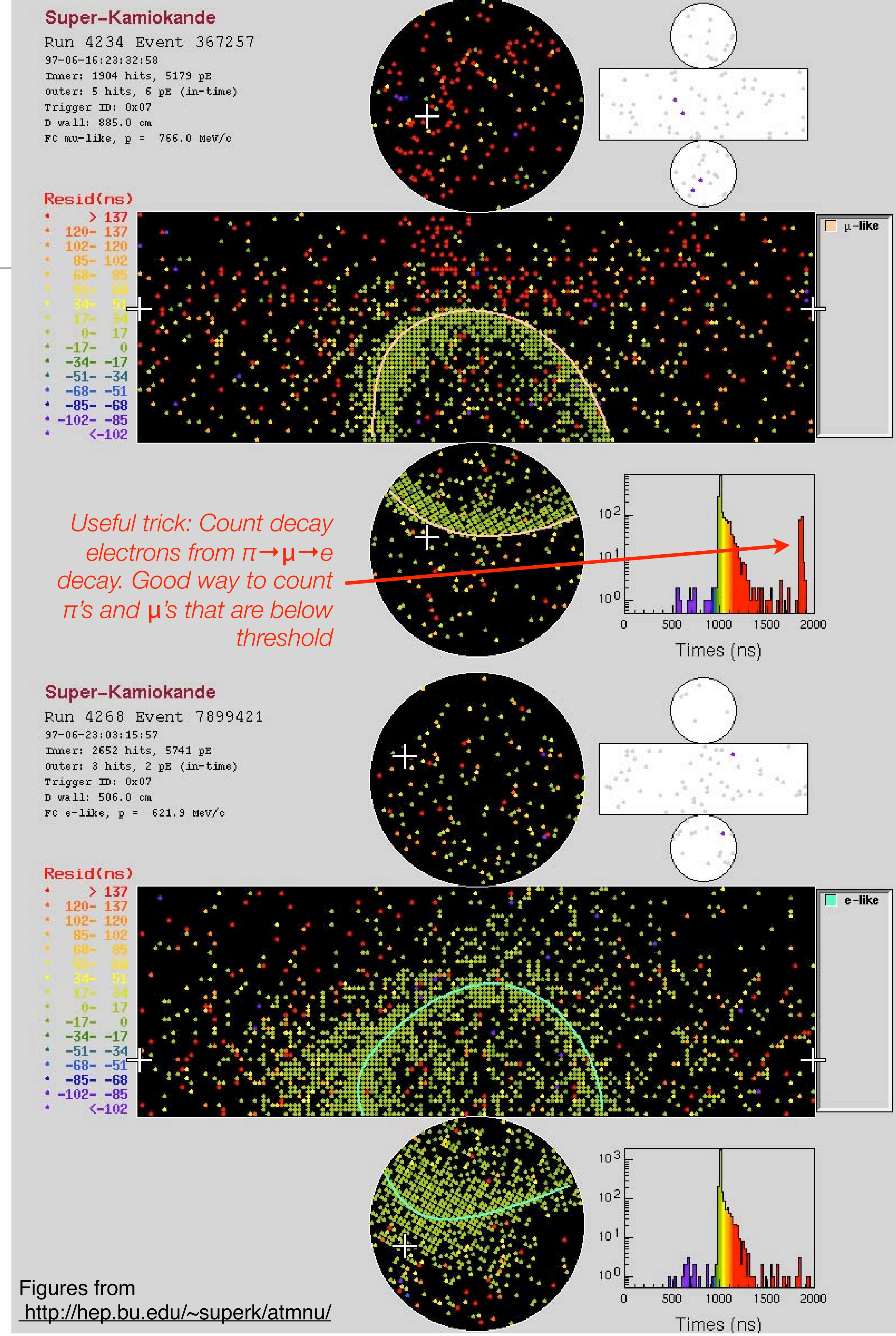

Useful trick: Count decay electrons from π→μ→e decay. Good way to count π’s and μ’s that are below threshold

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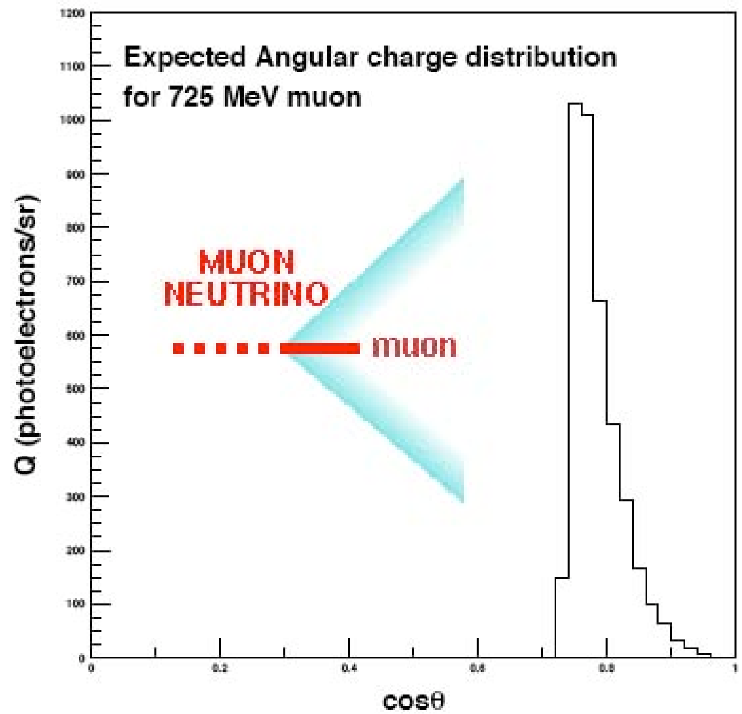

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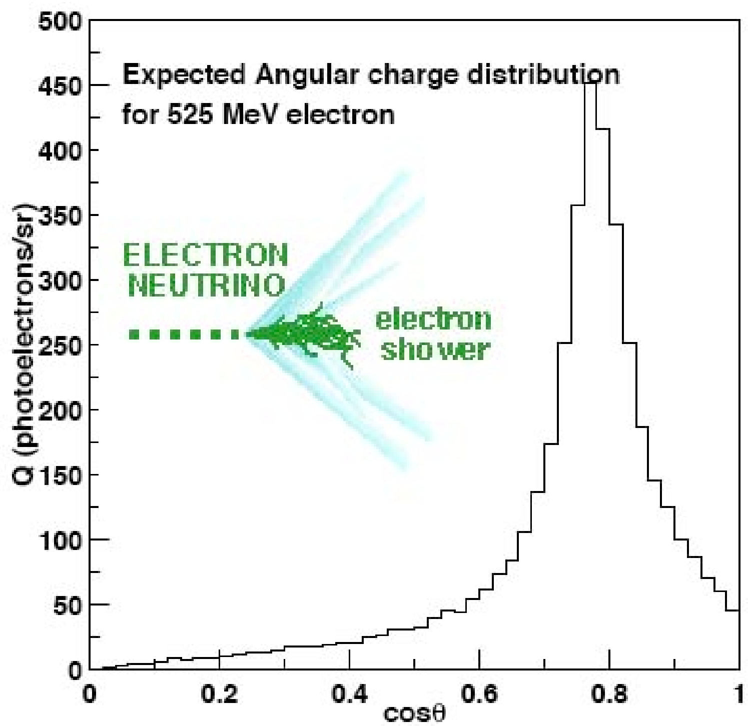

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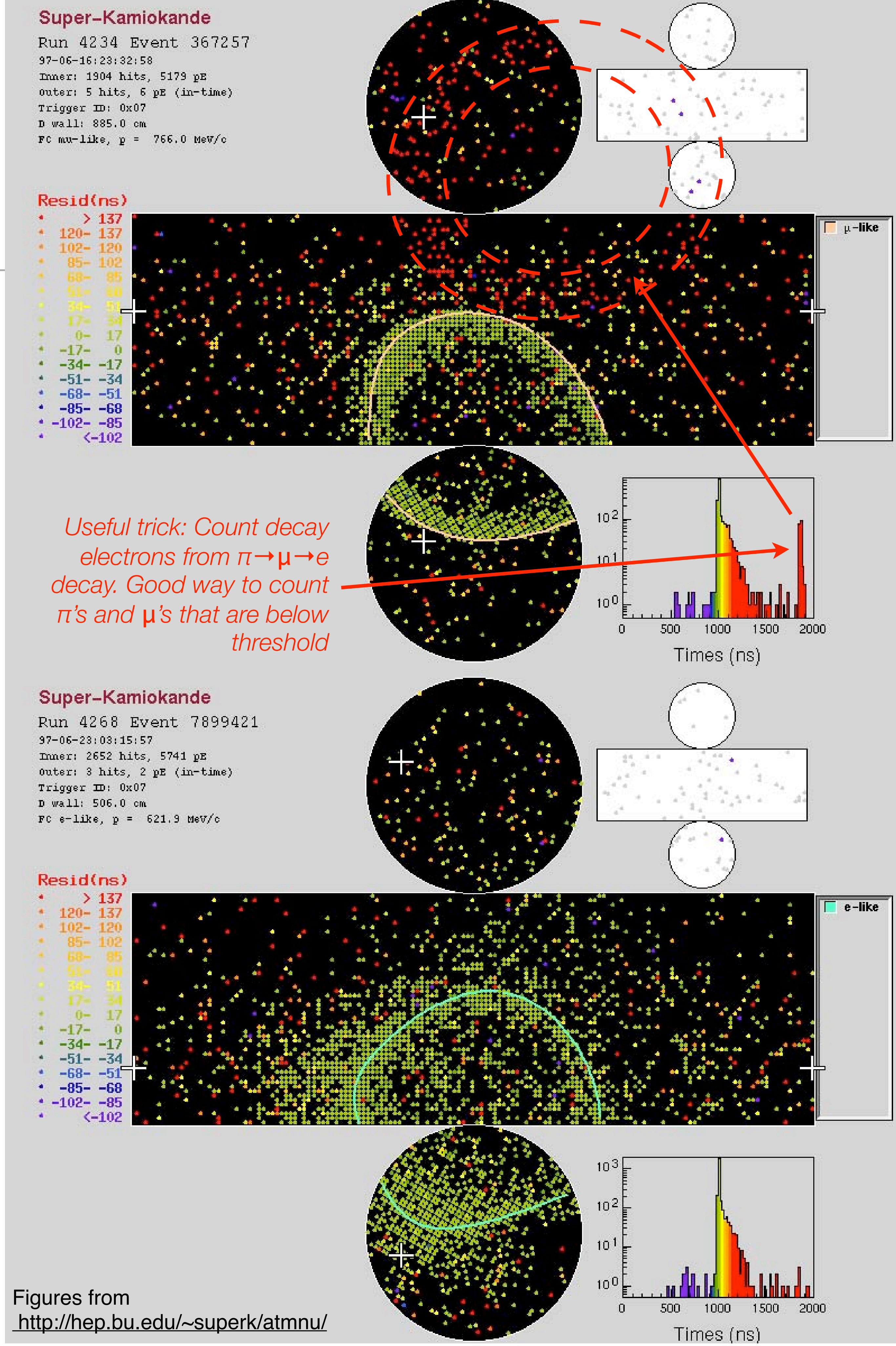

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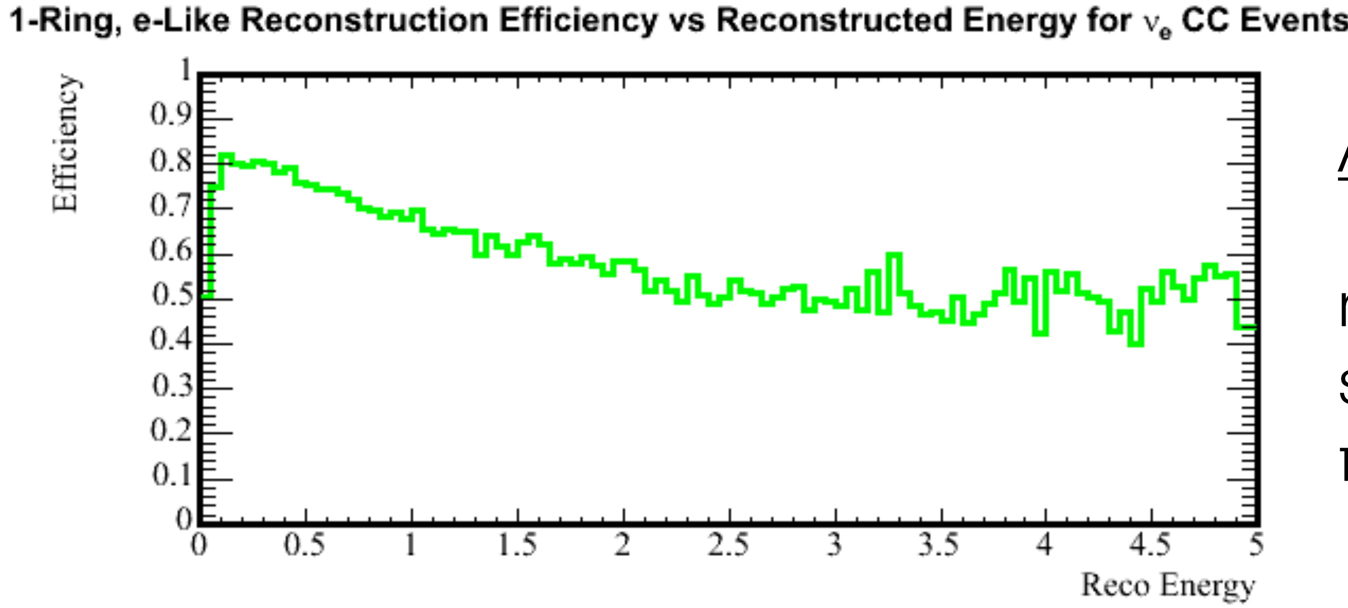
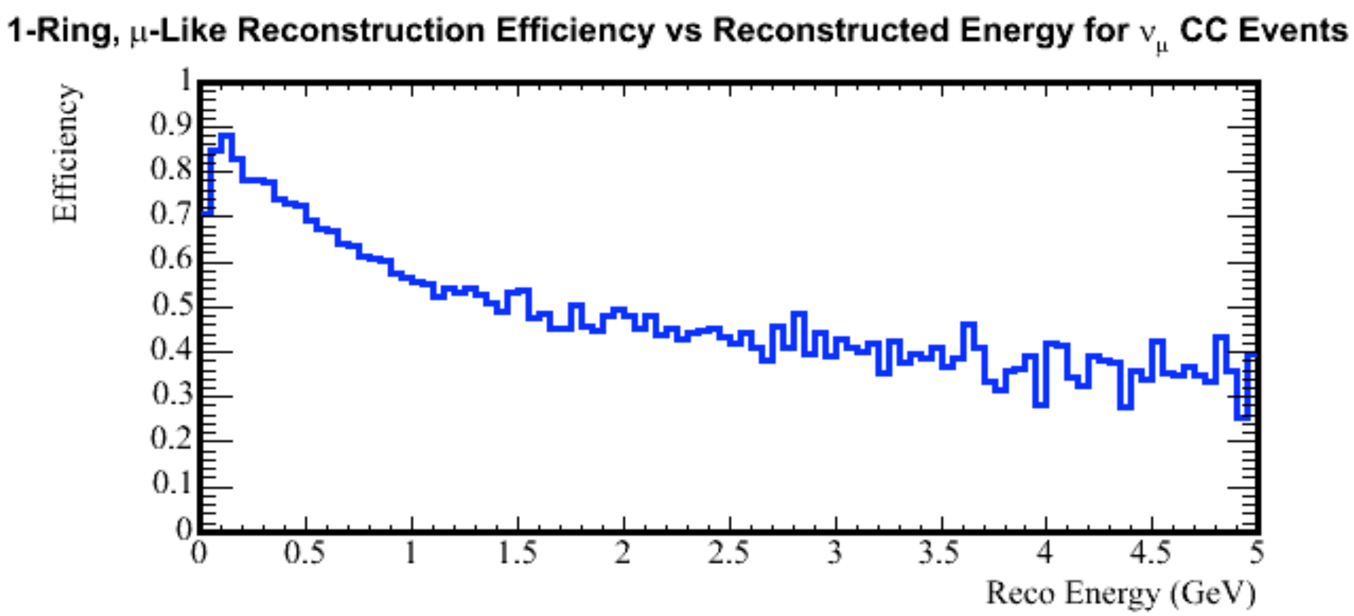
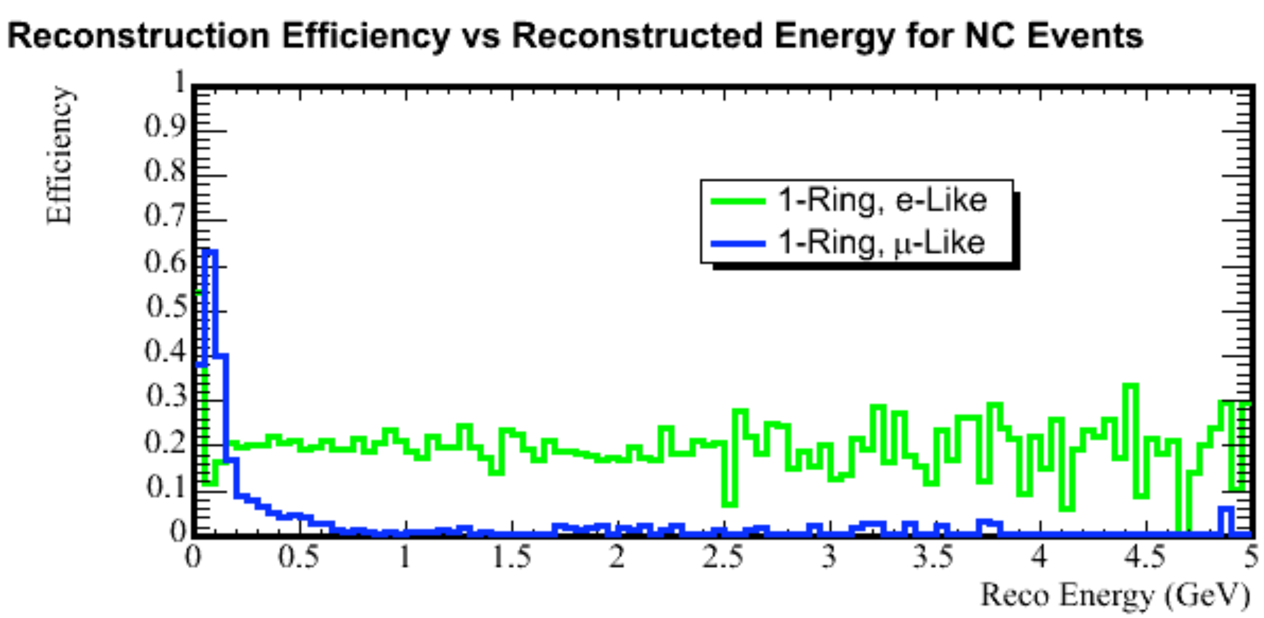




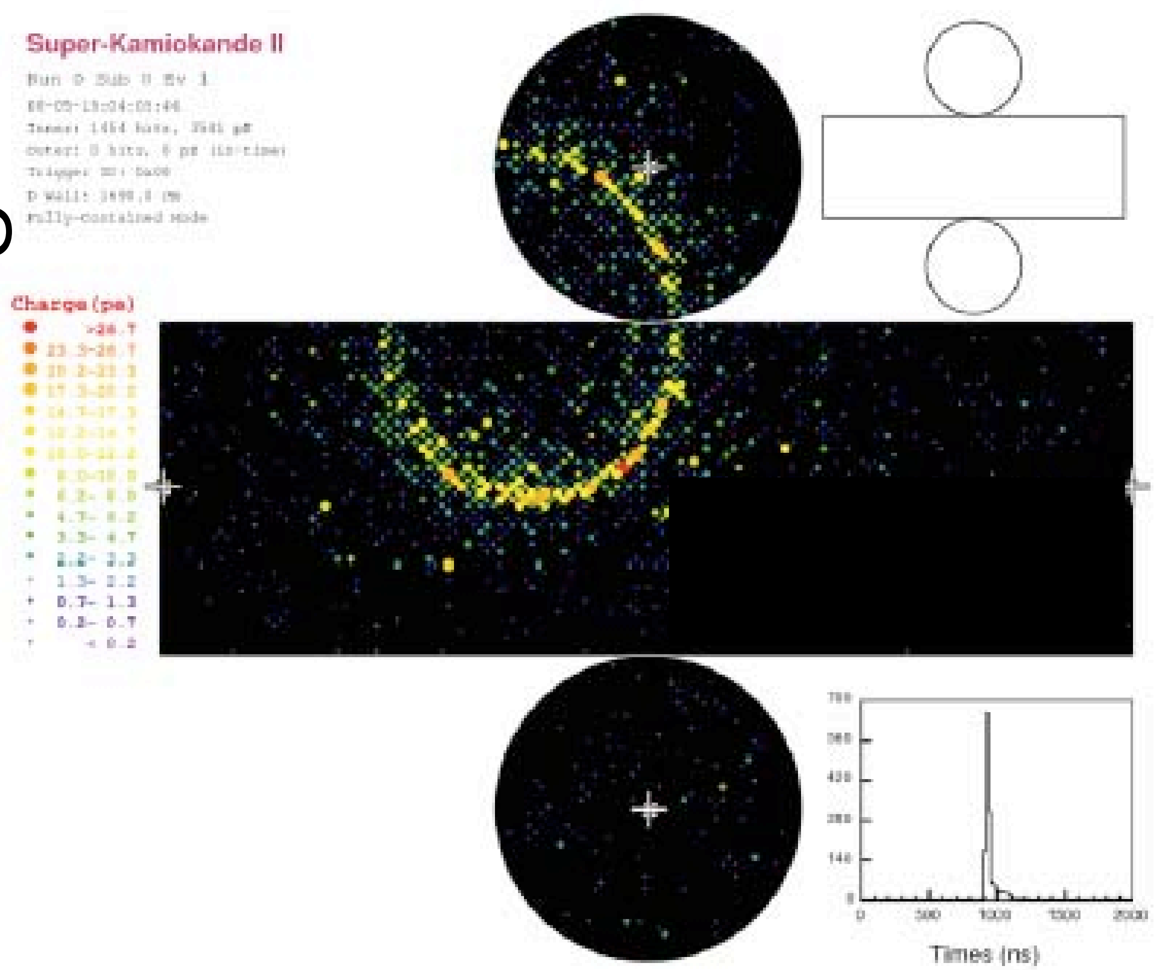


<u>Additional selections:</u>

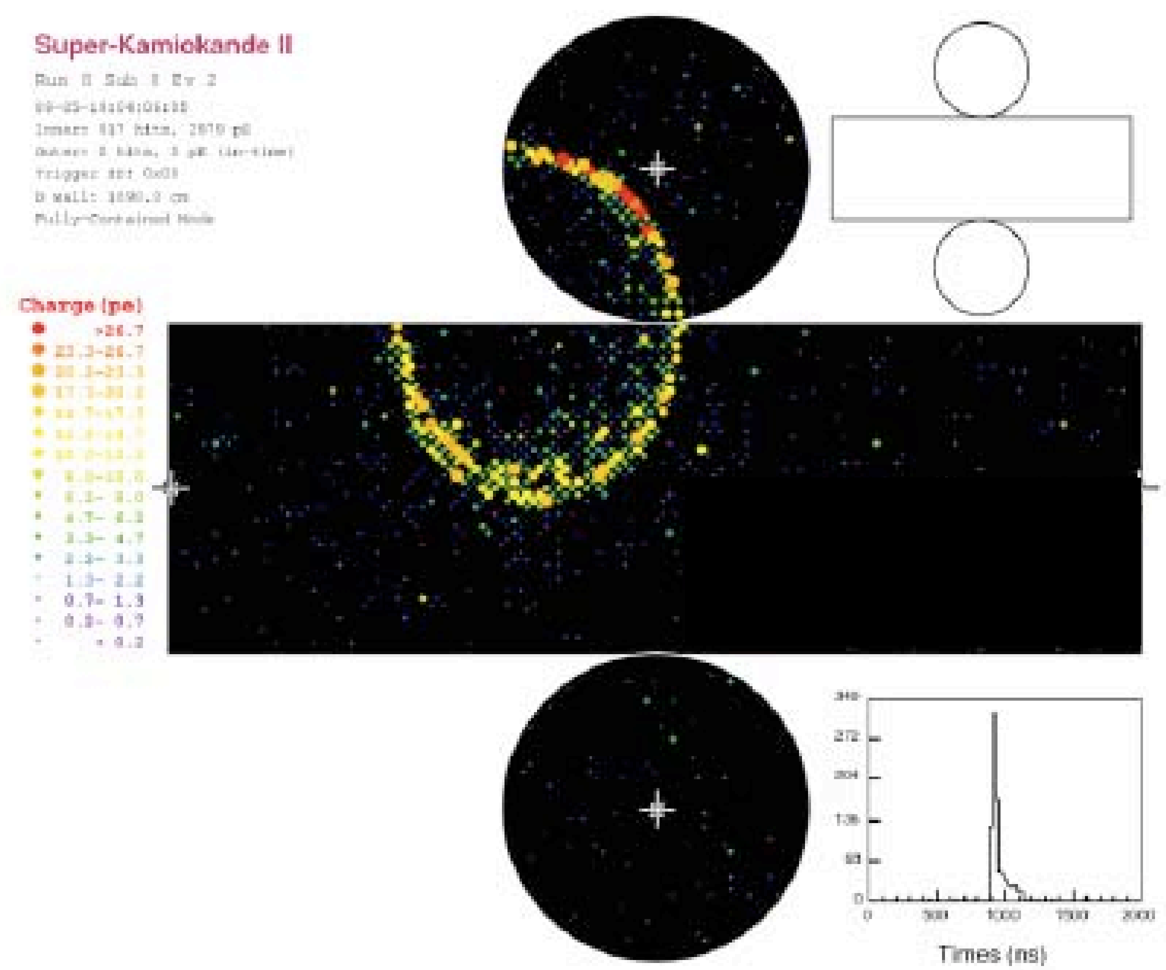
	CC ν_μ	NC	CC ν_e
no decay electrons:	14%	19%	76%
signal energy window (T2K)	1%	16%	58%
π^0 likelihood fit	0.4%	10%	42%

Notice: NC events much more likely to be e-like than **μ**-like due to π^0 production

20% coverage

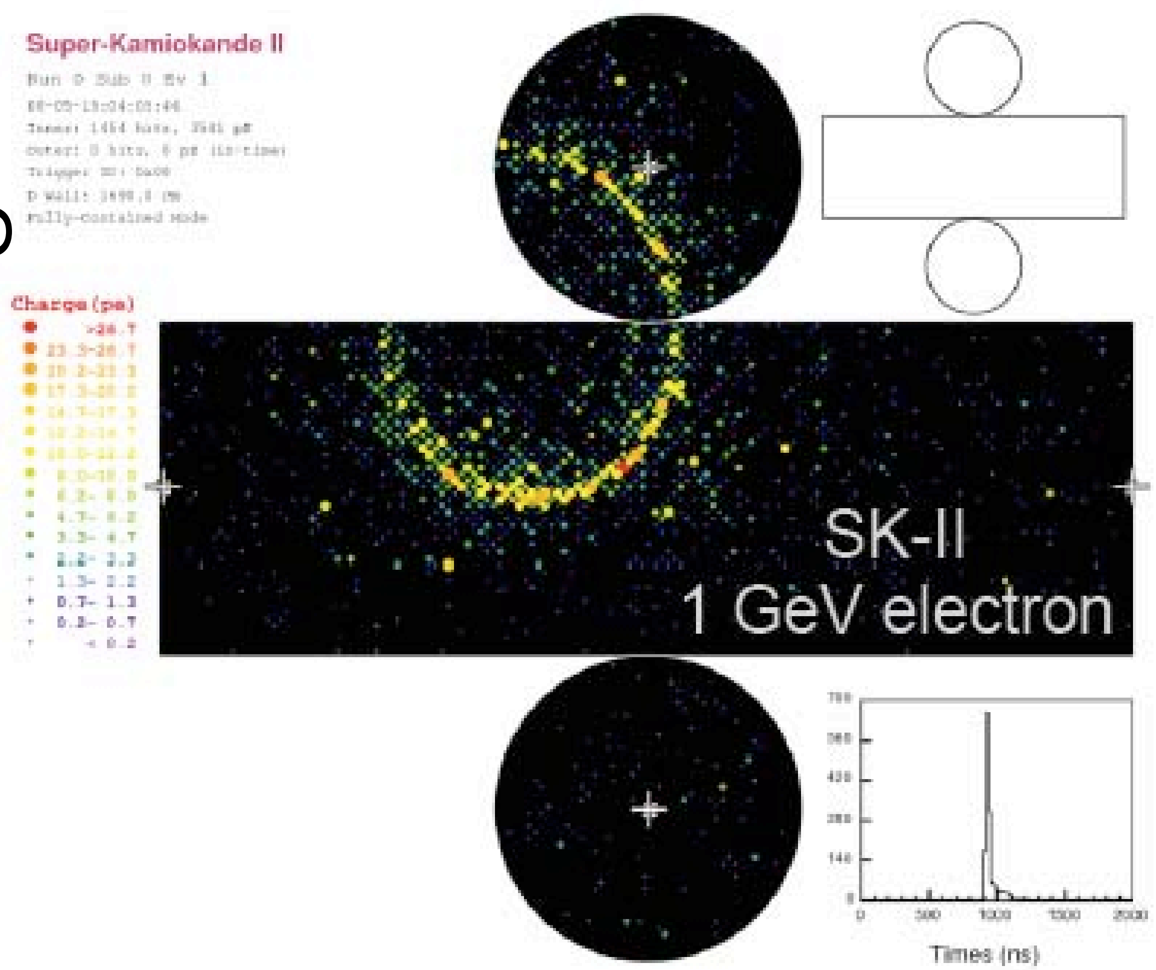


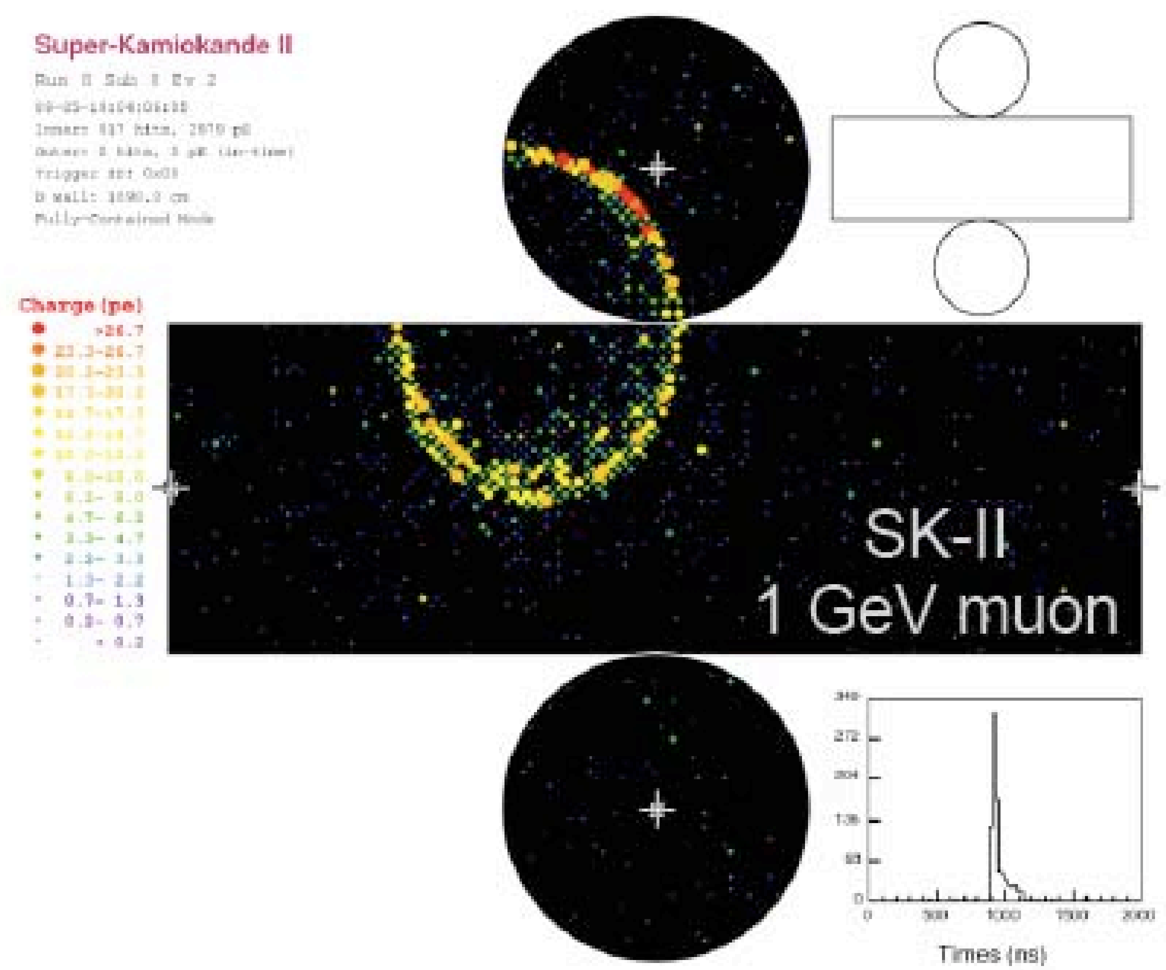
Super-Kamiokande II
Charge (pe)
Times (ns)

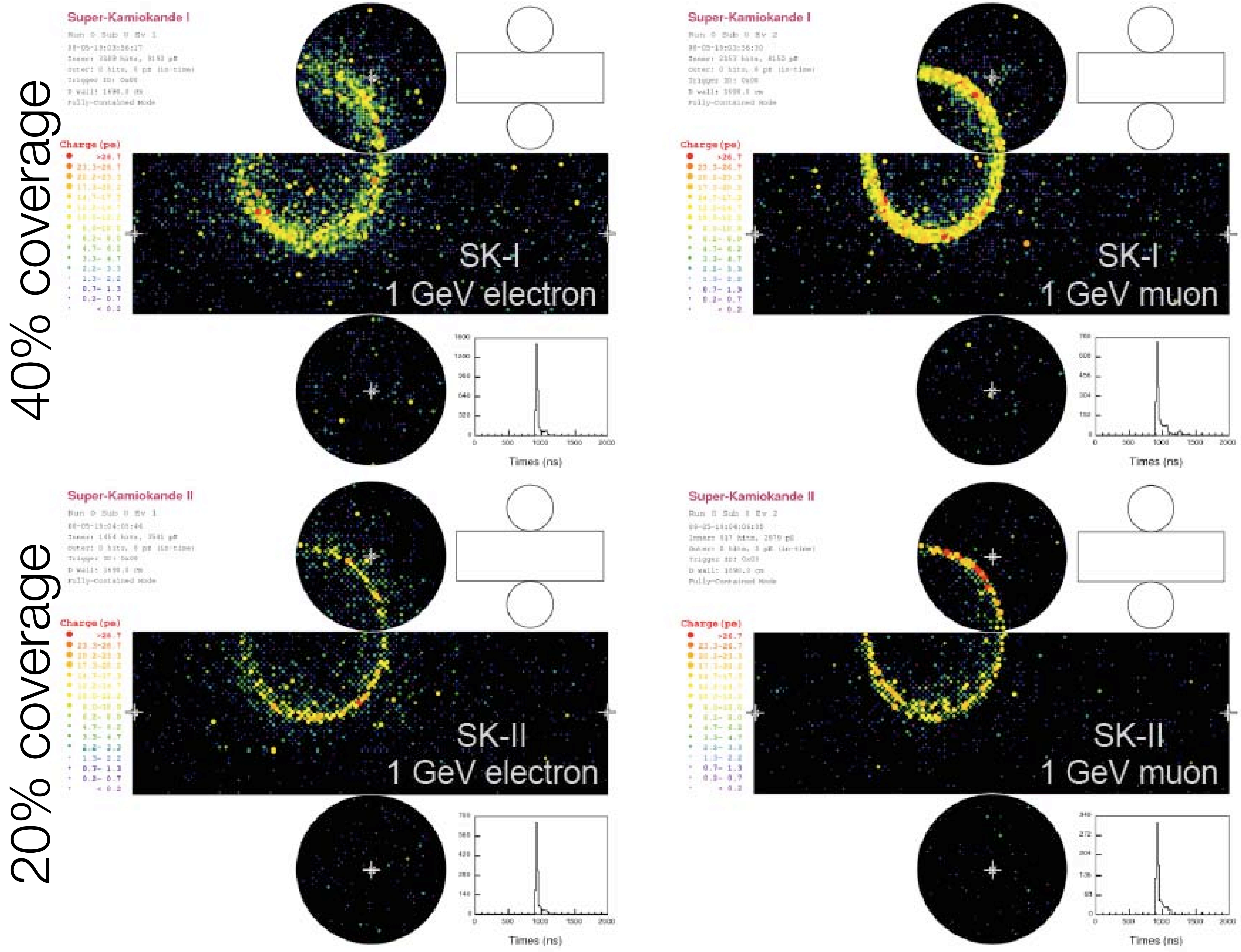


Super-Kamiokande II
Charge (pe)
Times (ns)

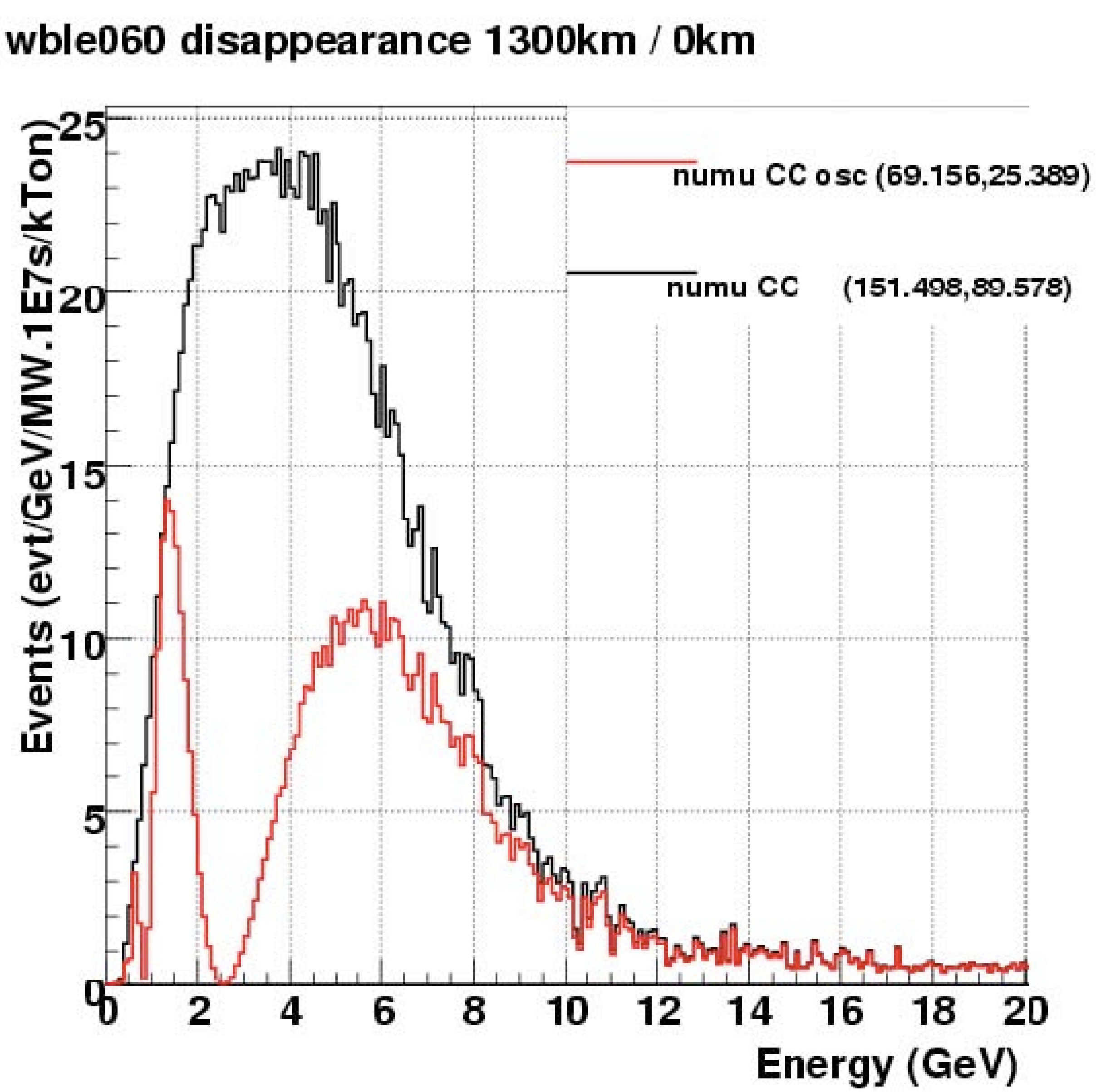
20% coverage

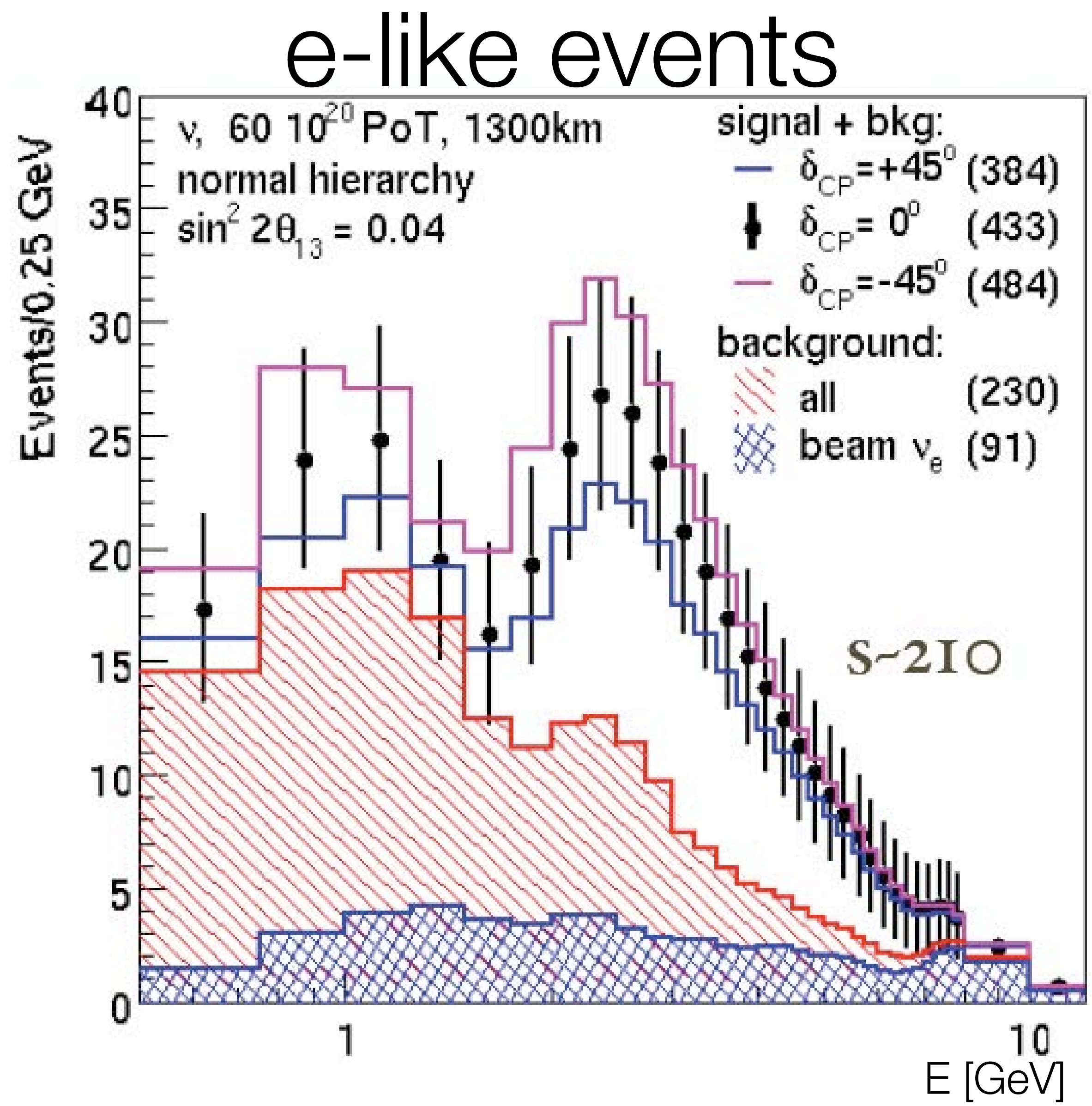

Super-Kamiokande II
Charge (pe)
SK-II
1 GeV electron
Times (ns)


Super-Kamiokande II
Charge (pe)
SK-II
1 GeV muon
Times (ns)


40% coverage
20% coverage
Super-Kamiokande I
Charge (pe)
SK-I
1 GeV electron
Times (ns)
Super-Kamiokande I
Charge (pe)
SK-I
1 GeV muon
Times (ns)
Super-Kamiokande II
Charge (pe)
SK-II
1 GeV electron
Times (ns)
Super-Kamiokande II
Charge (pe)
SK-II
1 GeV muon
Times (ns)

Pushing the technology: Sub-GeV to Multi-GeV

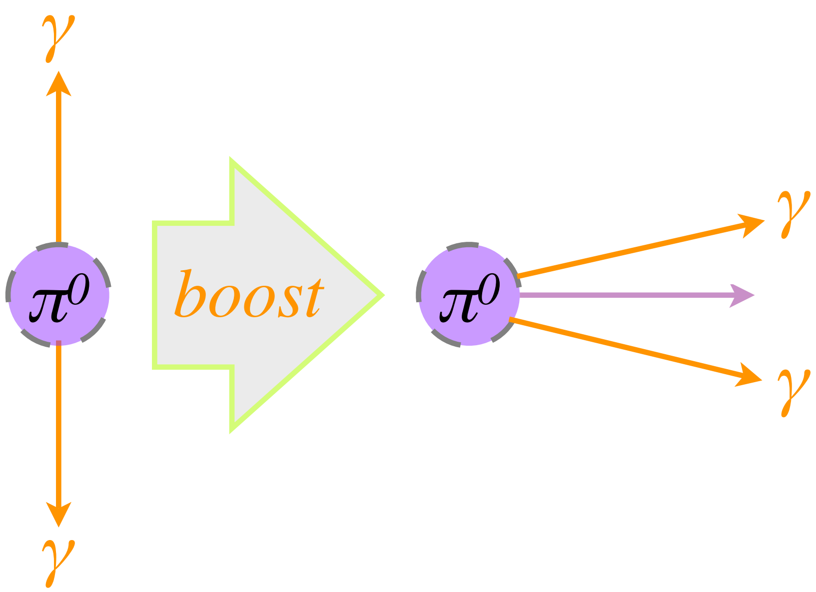


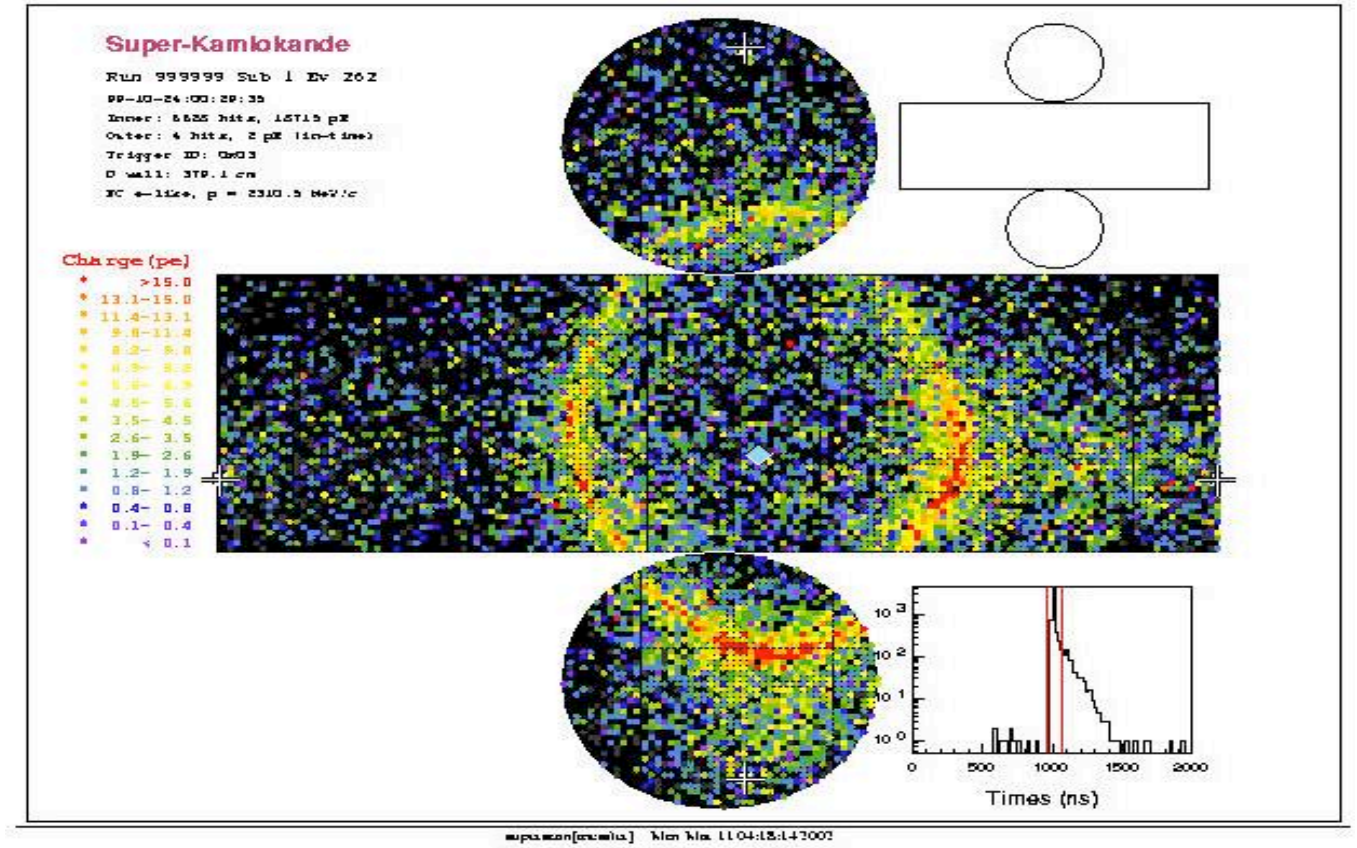


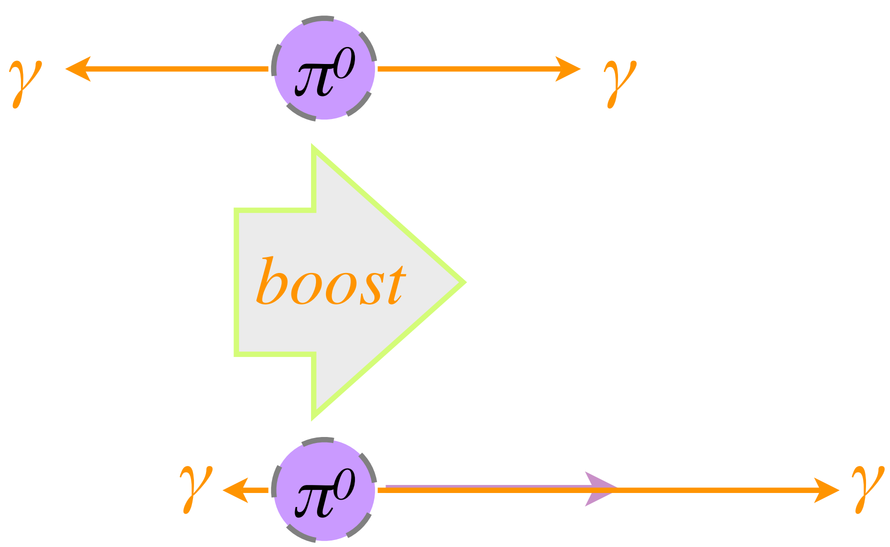
100 kt water detector in multi-GeV 2 MW wide band beam Fermilab to Homestake

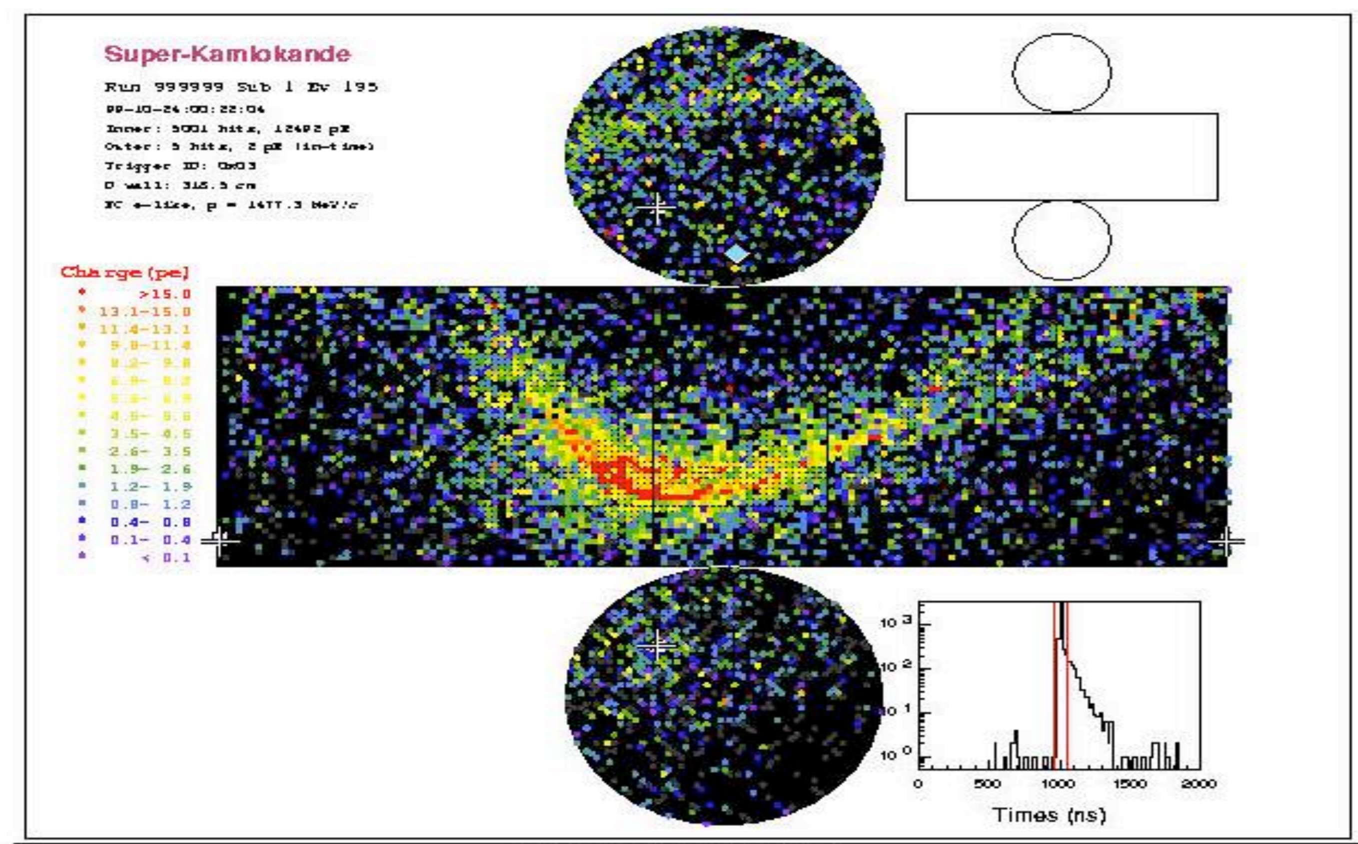
2 GeV visible energy
One is signal, the other background

π0 decay at high energy



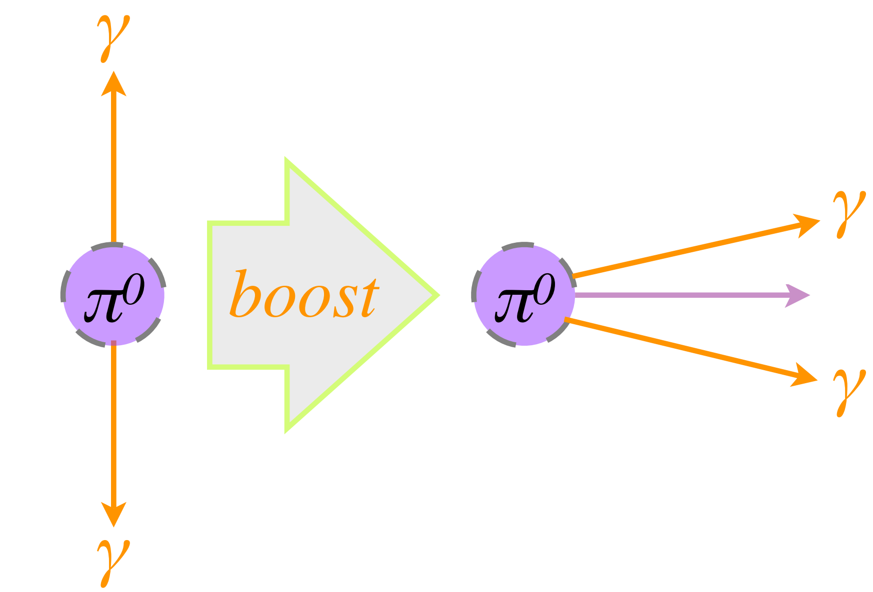


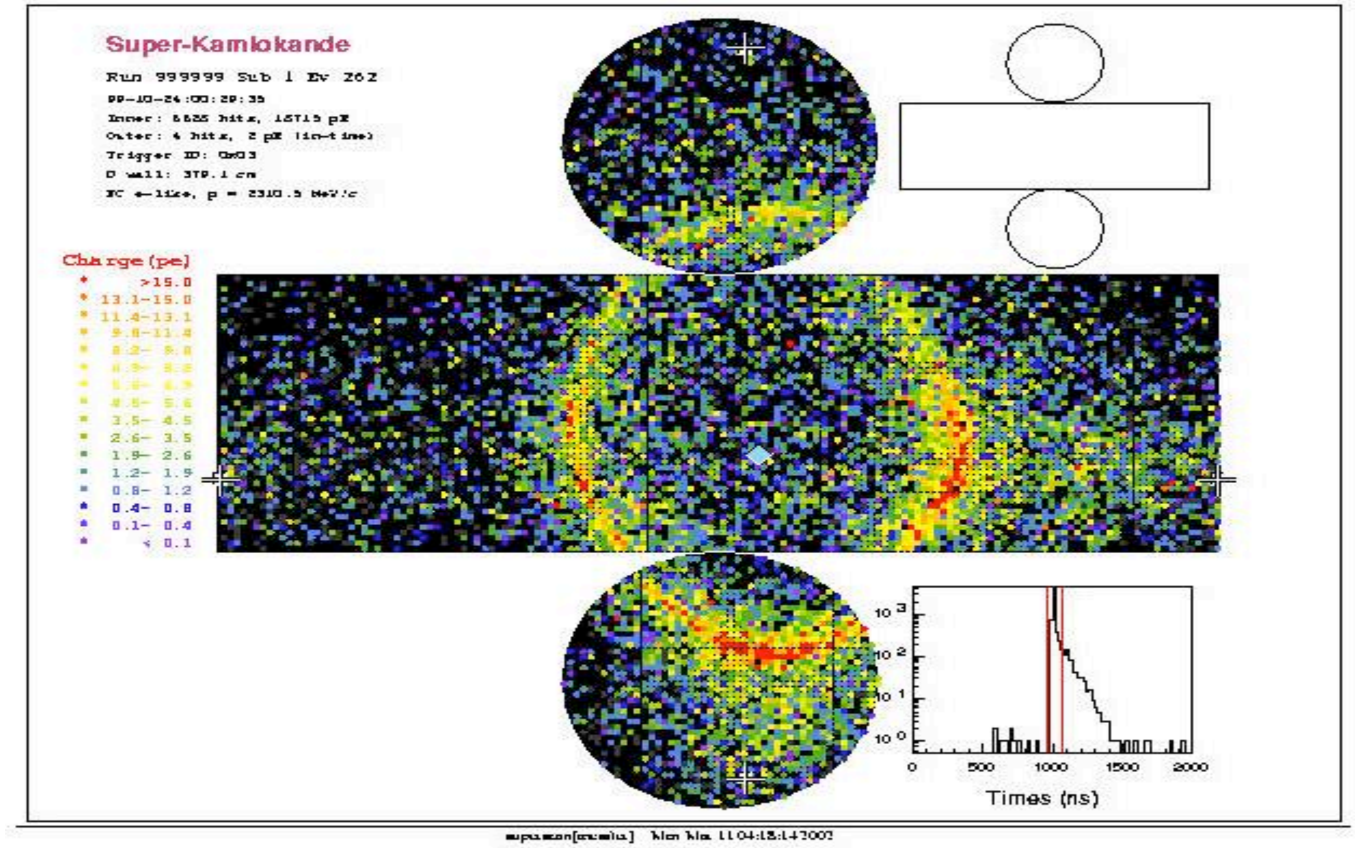




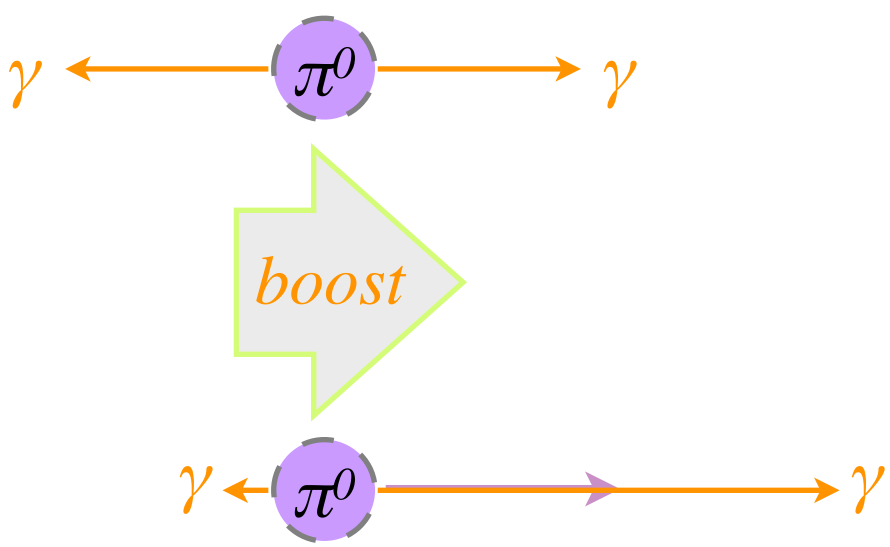
2 GeV visible energy
One is signal, the other background

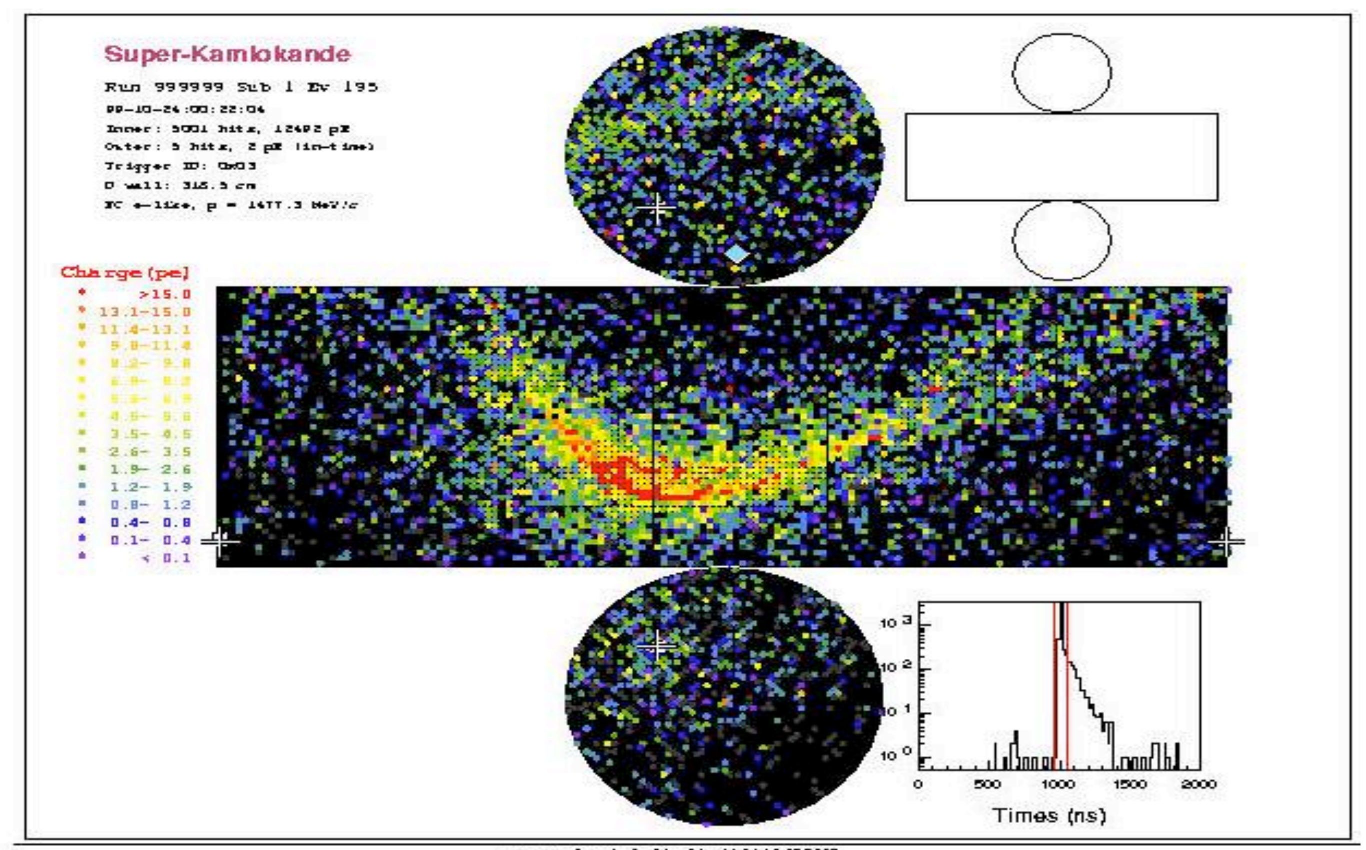
π^0 decay at high energy





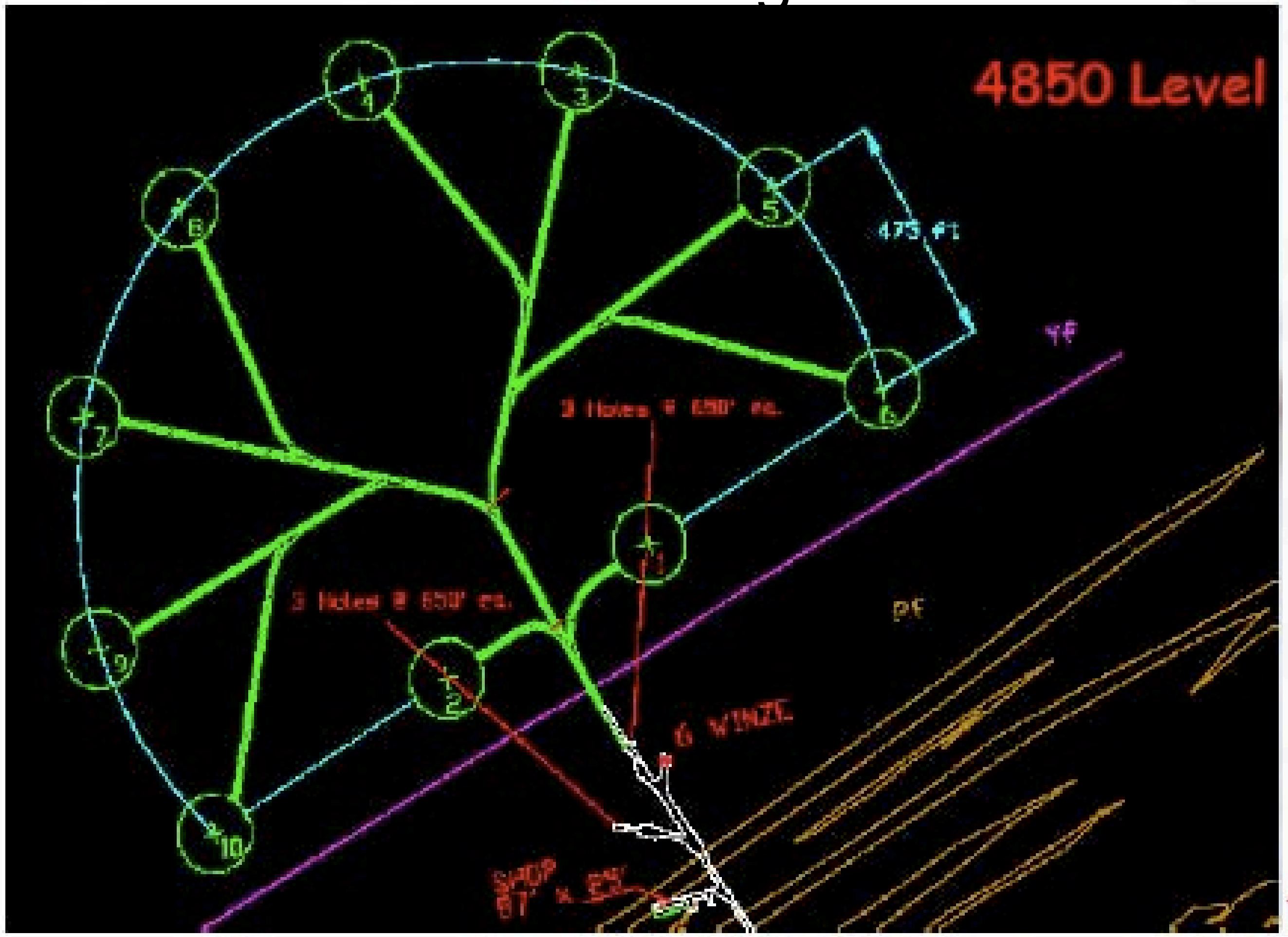
ν_e CC



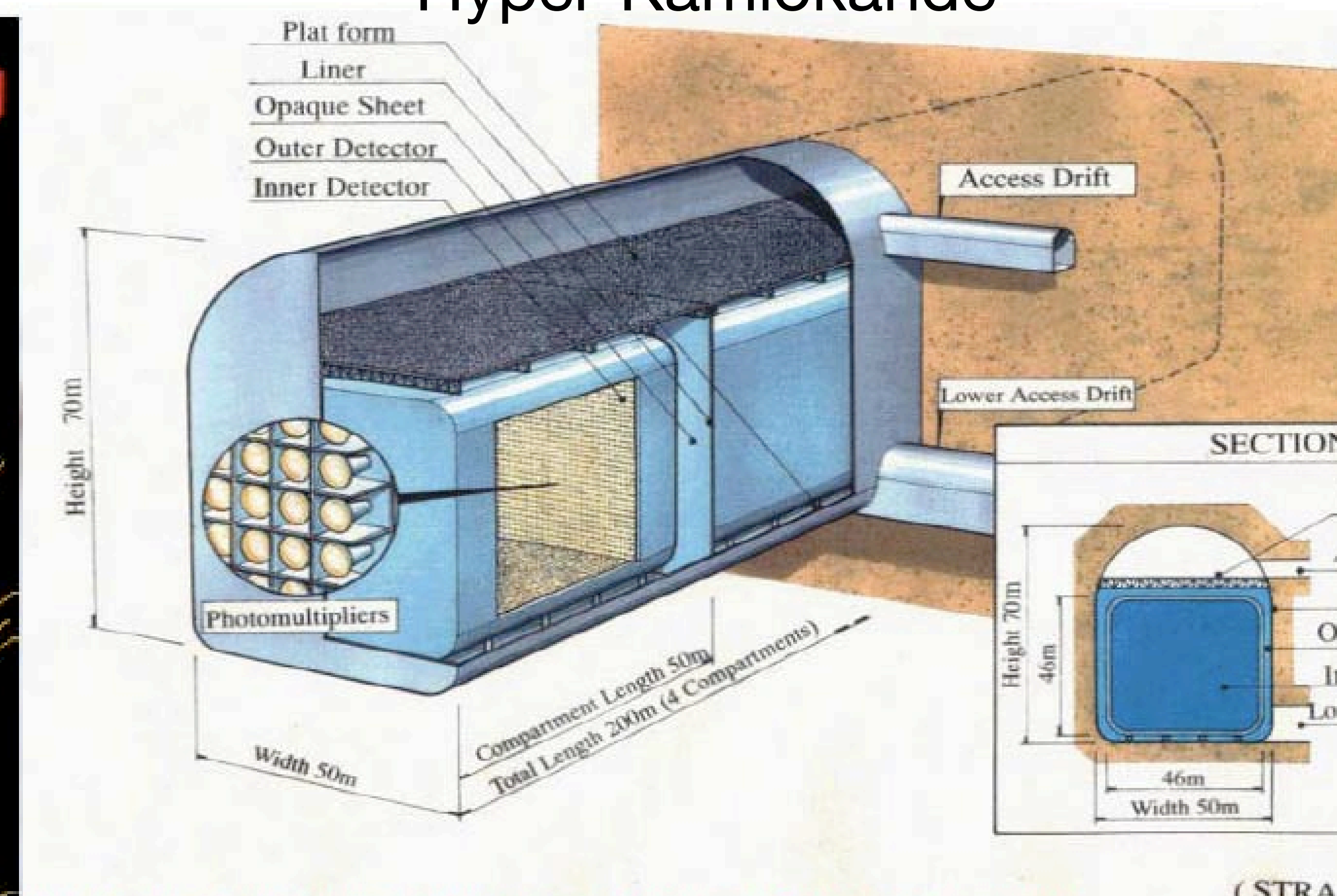


NC π^0

US DUSSEL Underground lab

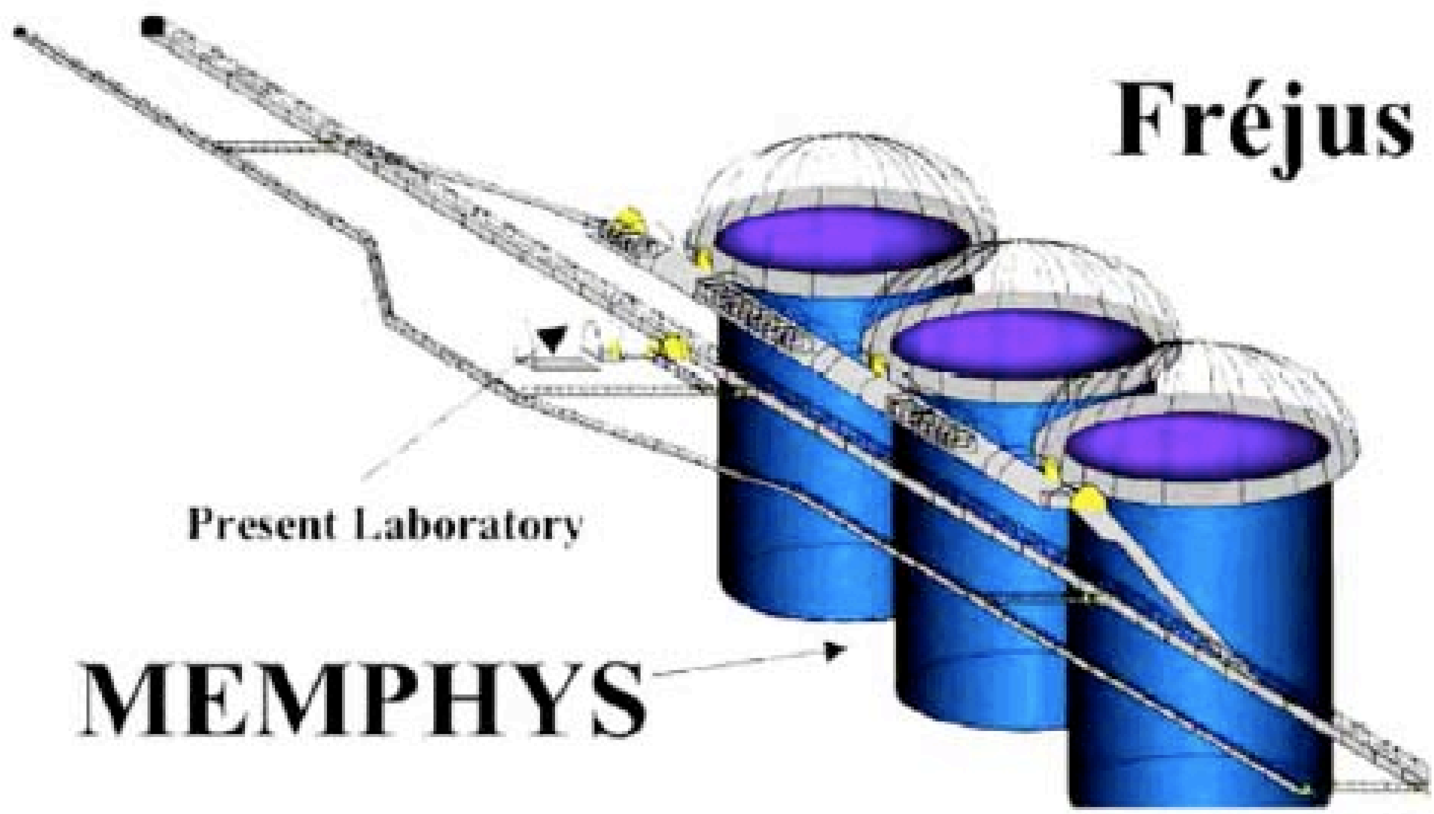


Hyper-Kamiokande



1 Mton fiducial volume: Total Length 800m (16 Compartments)

Megaton Scale Water Cherenkov Detectors



20% or 40% Photocathode coverage?

PMT's cost ~$3K USD and are one of the schedule drivers for construction of very large water Cherenkov detectors. Can you live with fewer?

	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm (μ-like)	30 cm (e-like) / 29 cm (μ-like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% (μ-like)	0.69% (e-like) / 0.96% (μ-like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% (μ-like)	6.3% (e-like) / 4.0% (μ-like)
$p \to e^+\pi^0$ signal efficiency	40.8±1.2 ±6.1%	42.2±1.2 ±6.3%
$p \to e^+\pi^0$ background	0.39(±35%) events/100kty	0 events/100kty
$p \to K^+\nu$, γ tag signal efficiency	8.4±0.1 ±1.7%	4.7±0.1 ±1.0%
$p \to K^+\nu$, γ tag background	0.72(±28%) events/100kty	1.4(±30%) events/100kty
$p \to K^+\nu$, $\pi^+\pi^0$ signal efficiency	5.5±0.1 ±0.7%	5.7±0.1 ±0.4%
$p \to K^+\nu$, $\pi^+\pi^0$ background	0.59(±28%) events/100kty	1.0(±30%) events/100kty
T2K $CC\nu_e$ likelihood effic.	83.7% (±0.1% stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

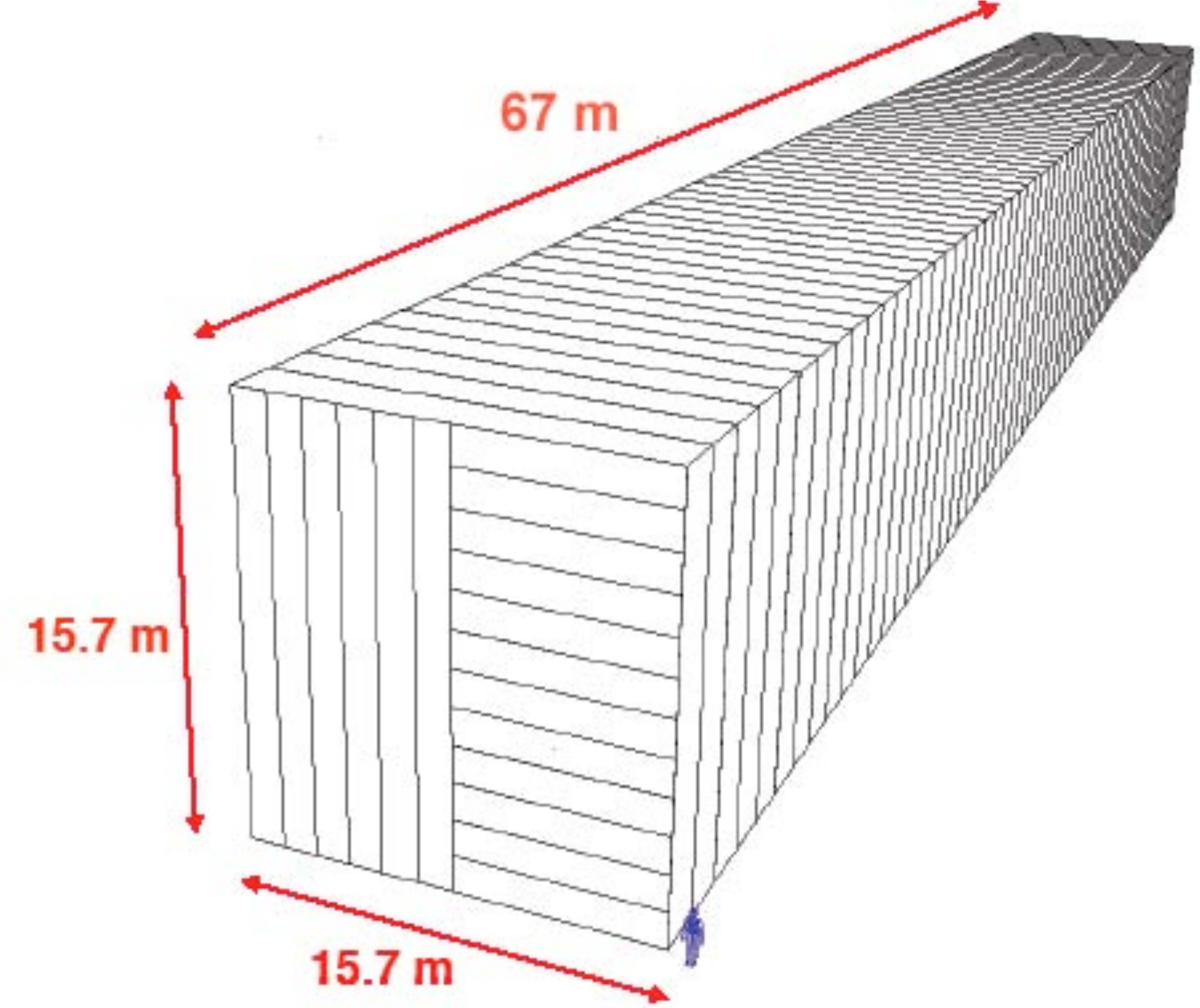
S.T. Clark, Ph.D. Thesis (2006)
F. Dufour, T2KK Workshop (2006)

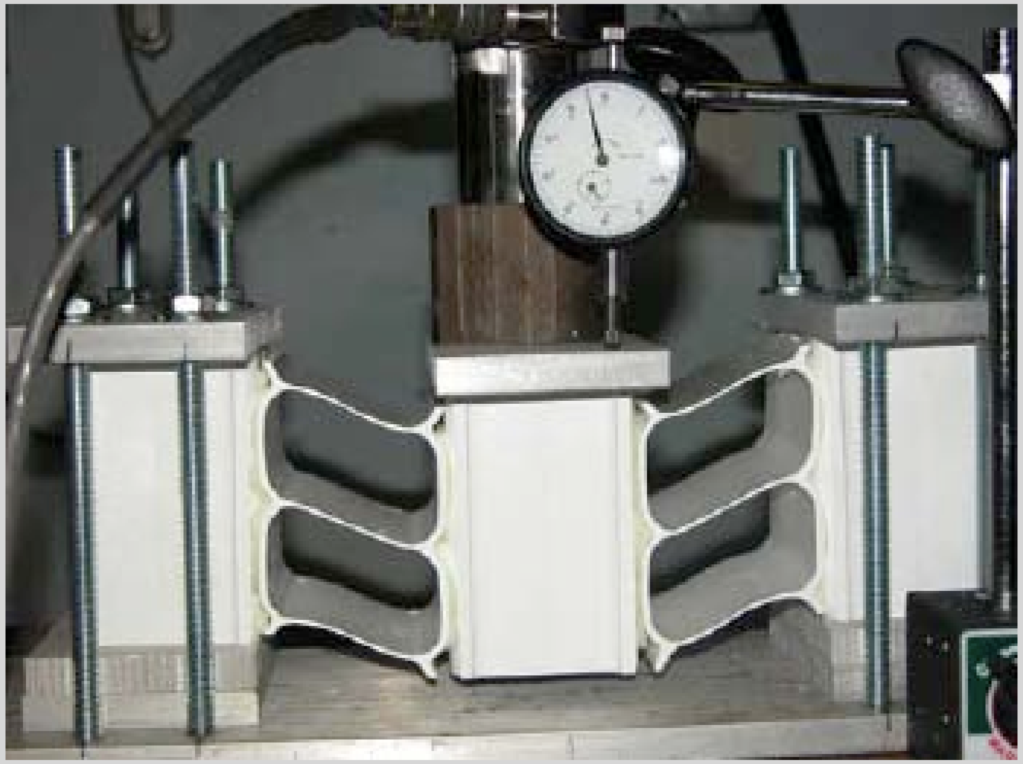
Preliminary numbers, for comparison purposes.
Final published efficiencies and BG may differ.

Totally Active Scintillator Detector (“TASD”)

The NOvA Experiment

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt “totally active” tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 215 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km





Top left: extrusions coming off the line
Bottom left: testing compressive strength
Above: Horizontal pieces for IPND

PVC Extrusions

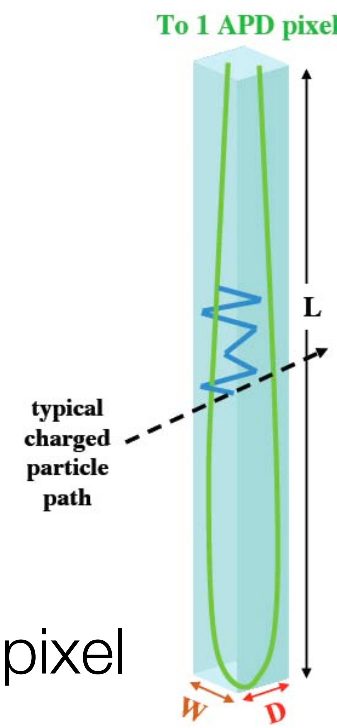
Detector design

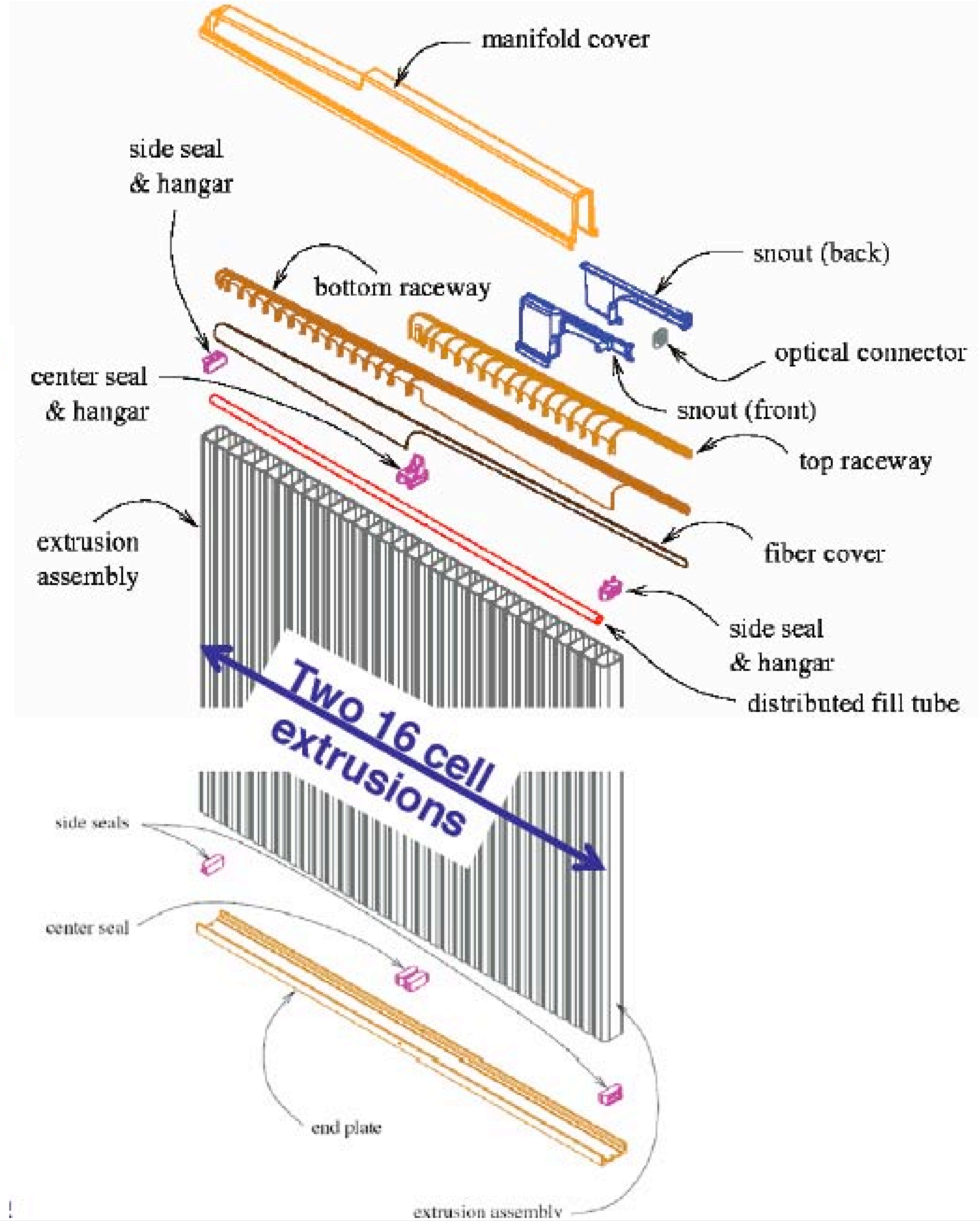
Liquid scintillator
(14.8M liters, 12.6 ktons)
Contained in 3.9 x 6.6 cell cells of length 15.7 m
-18 m attenuation length
-5.5% pseudocumene

Extruded PVC
(5.4 ktons)
15% anatase TiO_2 for high reflectivity

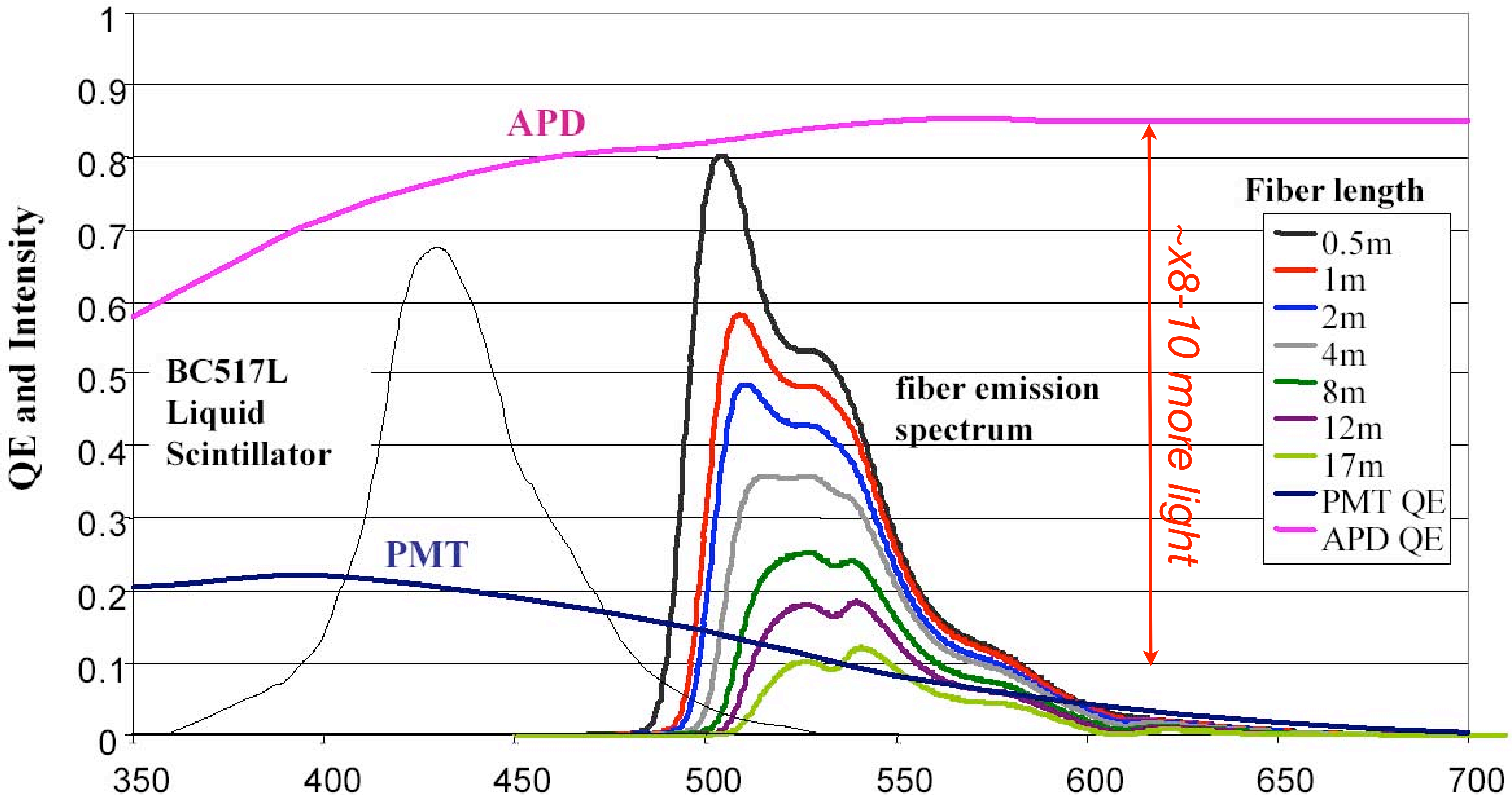
Wavelength shifting fiber
(18k km)
- 0.7 mm diameter
- Looped, both ends to same readout pixel

Avalanche photodiodes (APD)
(14k boards, 32 channels each)
- 85% quantum efficiency at long wavelengths
- Collect 30 photoelectrons per muon crossing at far end of cell





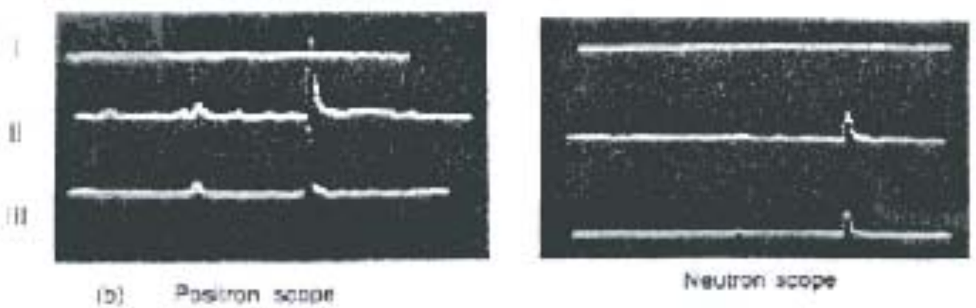
NOvA Fiber and Photodetector

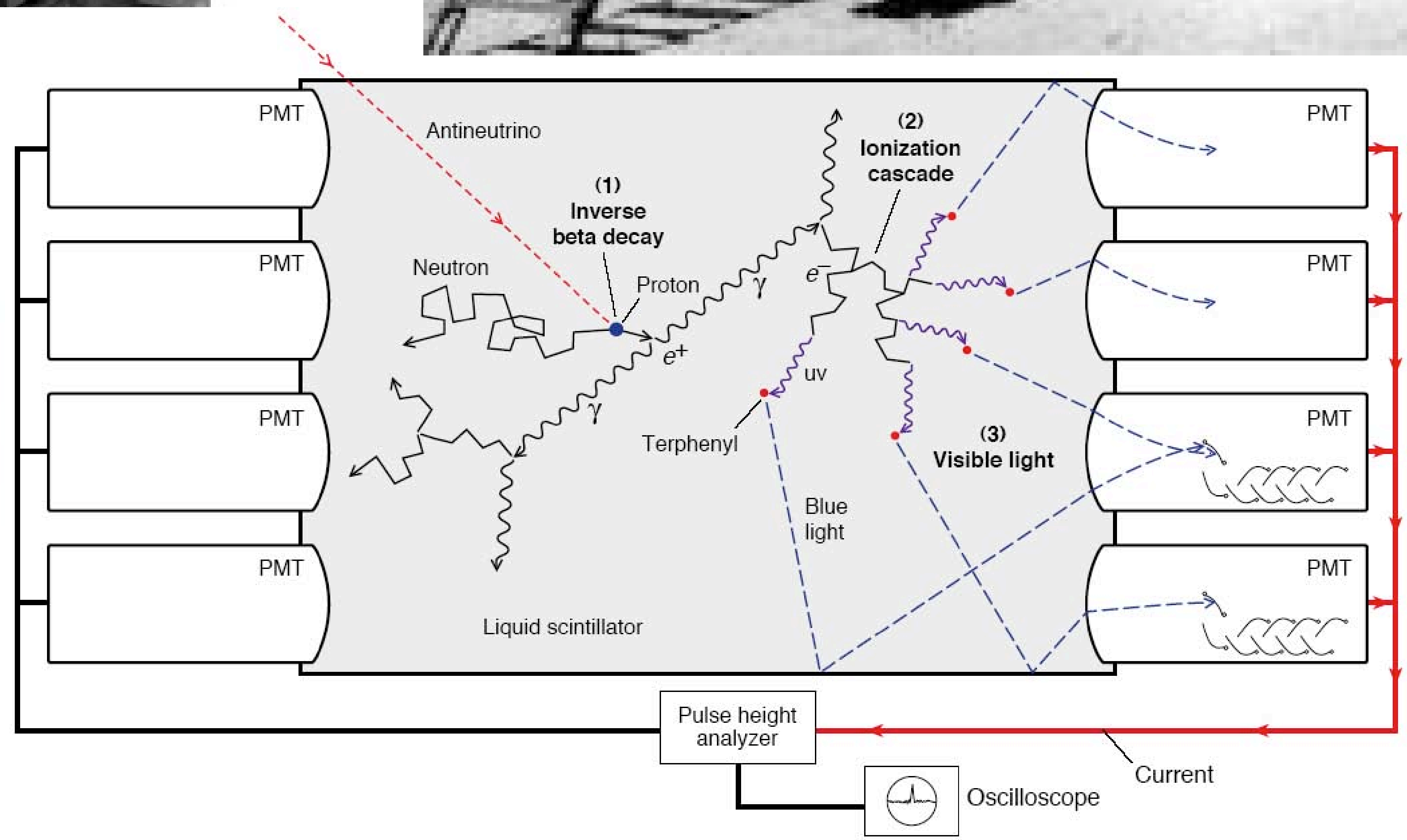


scintillation light ⟶ re-emission by fiber

The high QE of APD's, especially at long wavelength, is crucial to NOvA performance

Fred Reines and Clyde Cowan. 1995 Nobel to Reines for the detection of the neutrino





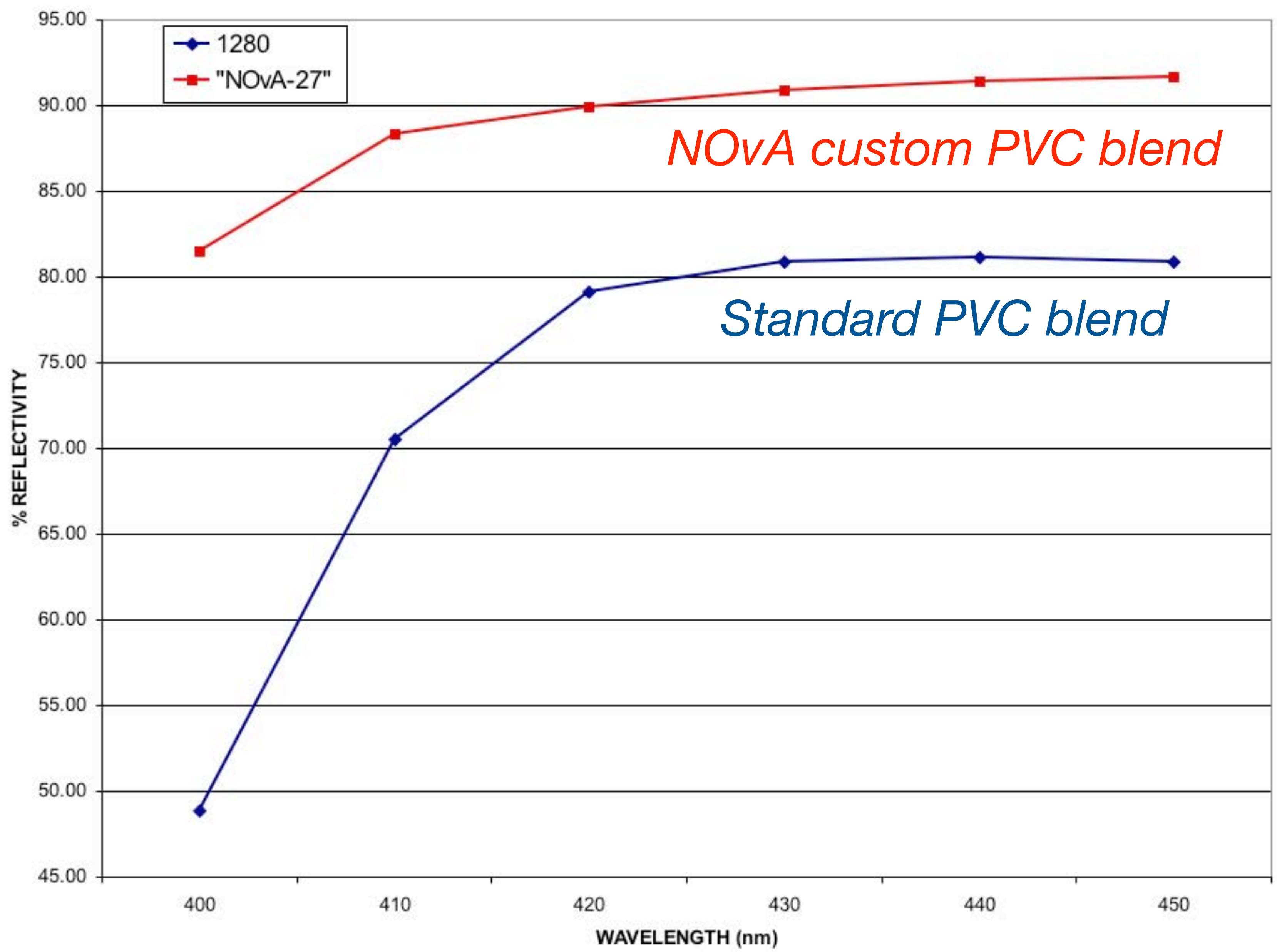
Los Alamos Science, Number 25 1997

Project Poltergeist, 1953

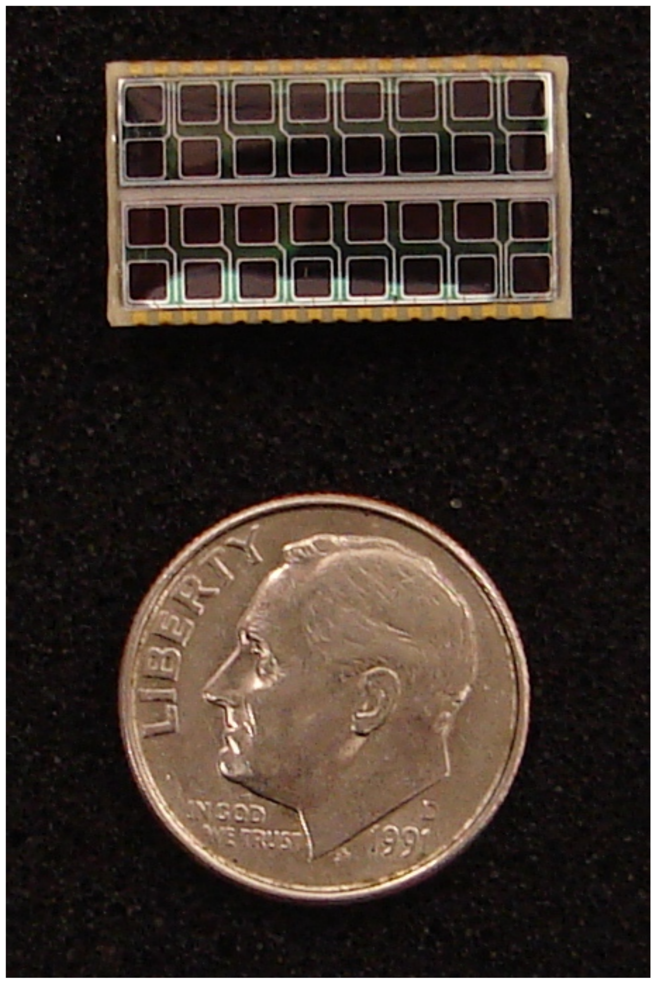
Wall reflectivity

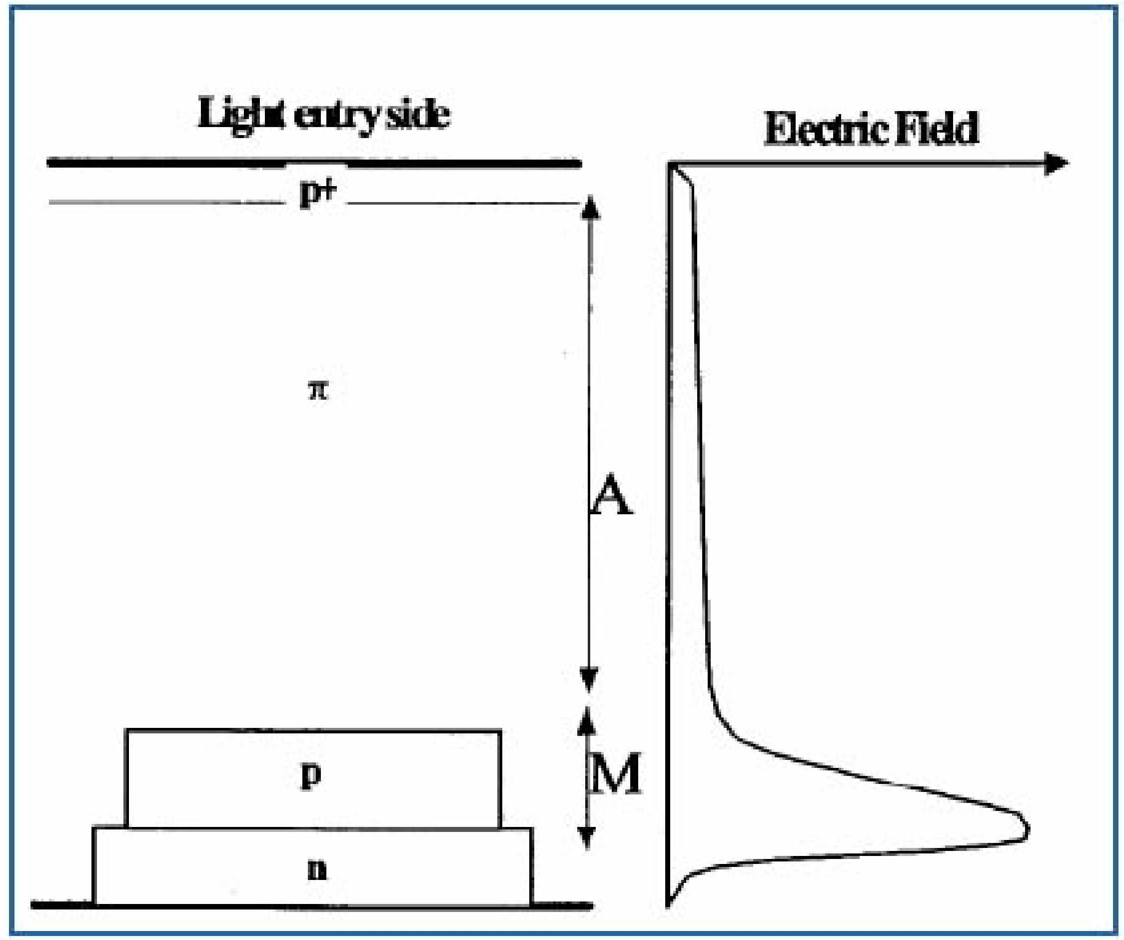
- In NOvA cell, a photon typically bounces off the cell walls 10 times before being captured by a fiber
- This makes the reflectivity of the cell wall of crucial importance to maximizing light output:
  - $0.8^{10} = 0.11$
  - $0.9^{10} = 0.35$

10% improvement in reflectivity yields factor 3 more light!



Avalanche photo diodes (APD)





Absorption region

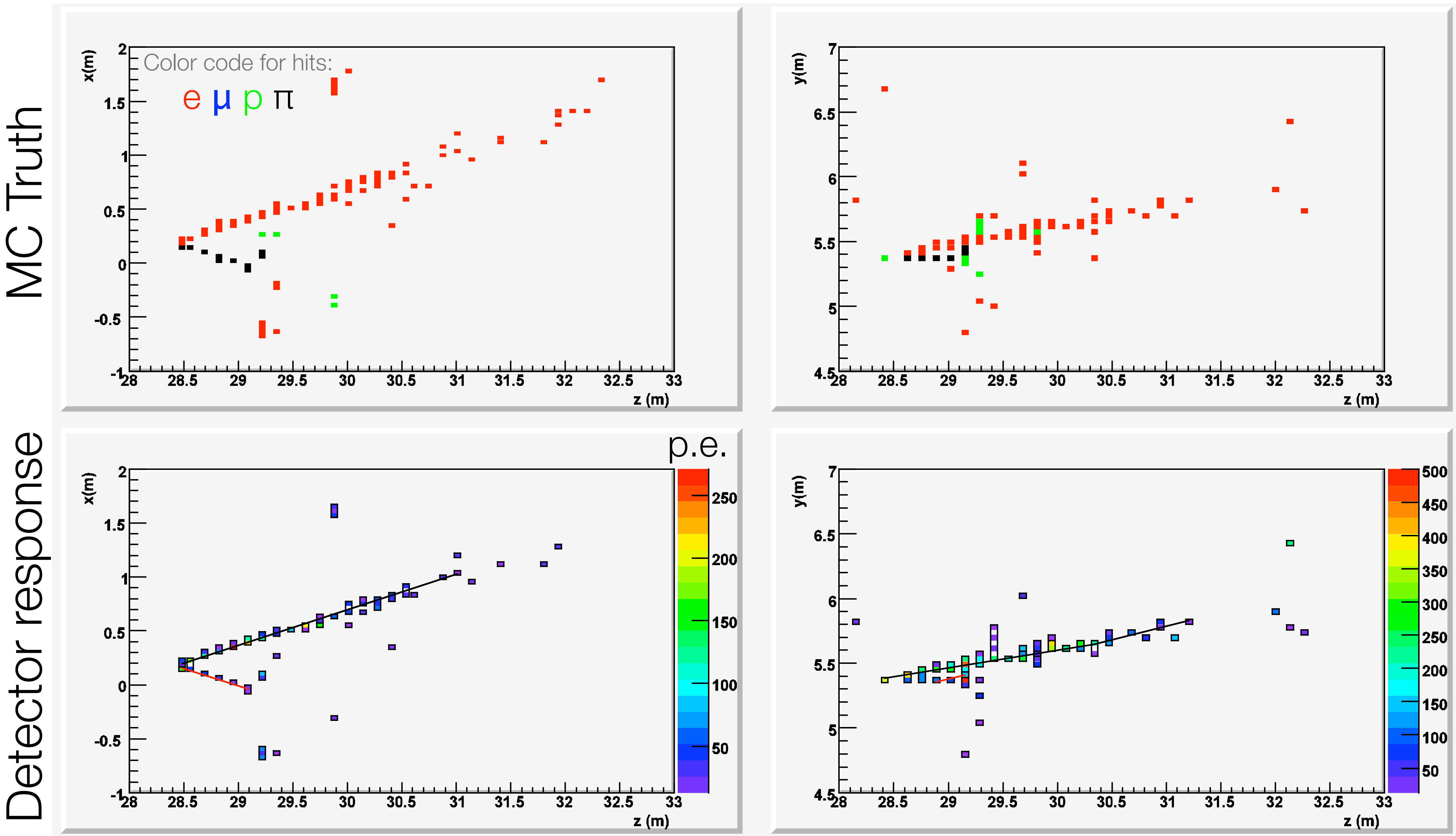
Multiplication region

High (80%) quantum efficiency even into UV

Large dark currents - must be cooled to -15^{o}C to get noise down to ~10 pe equivalent

Low gains, x100

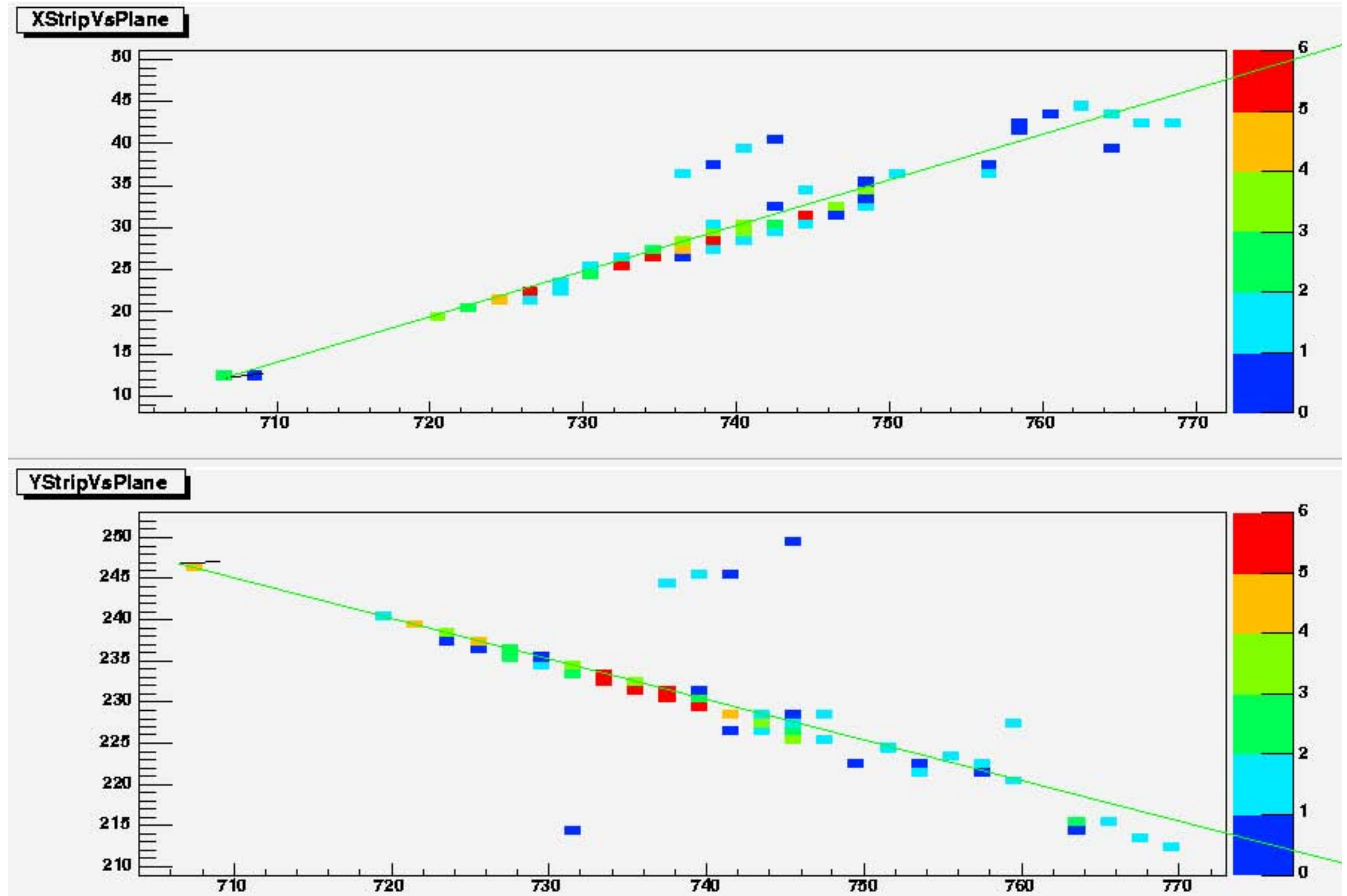
ν_e (2.4 GeV) + N → e^- (1.8 GeV) + X (Res)

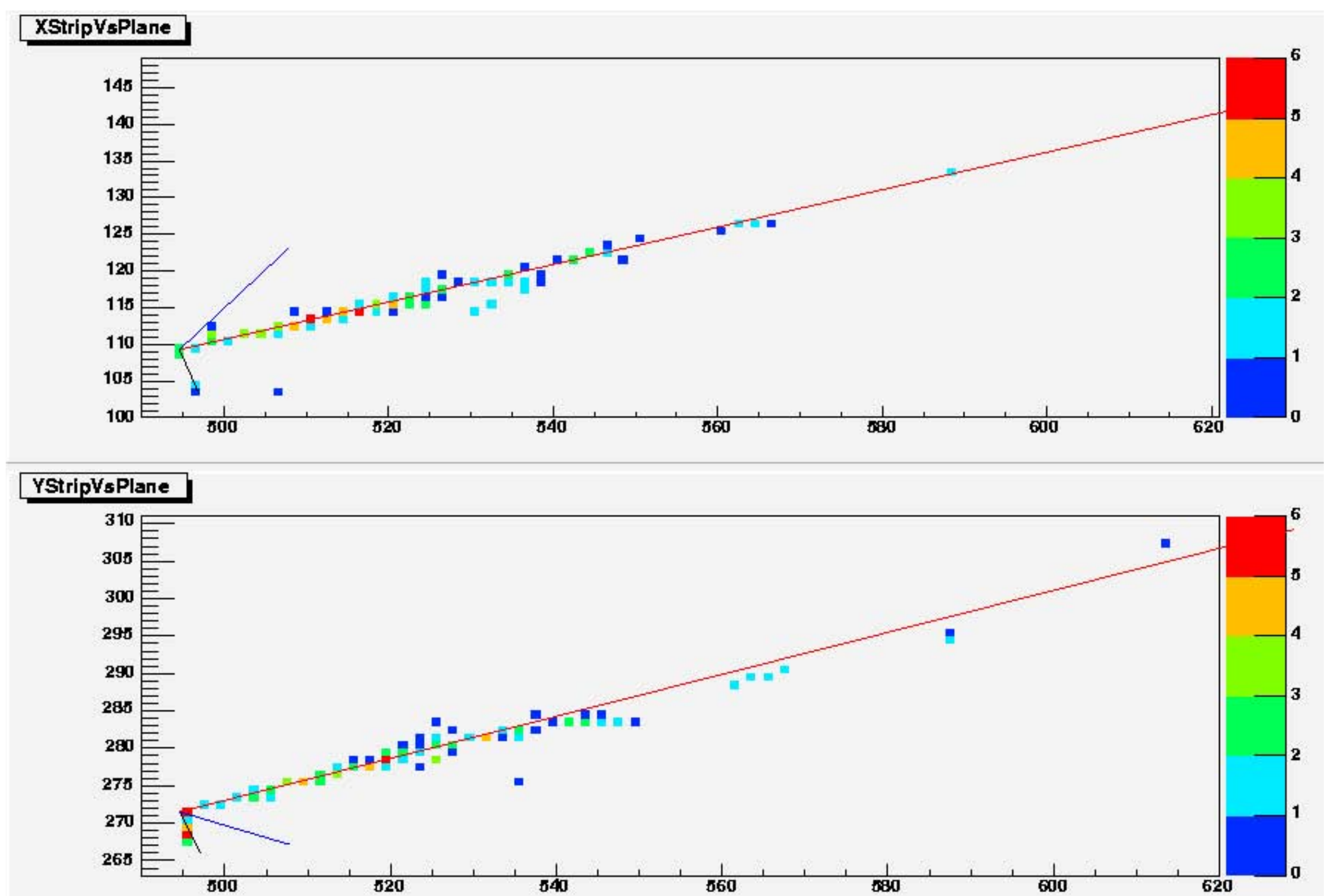


Electron neutrino signal event

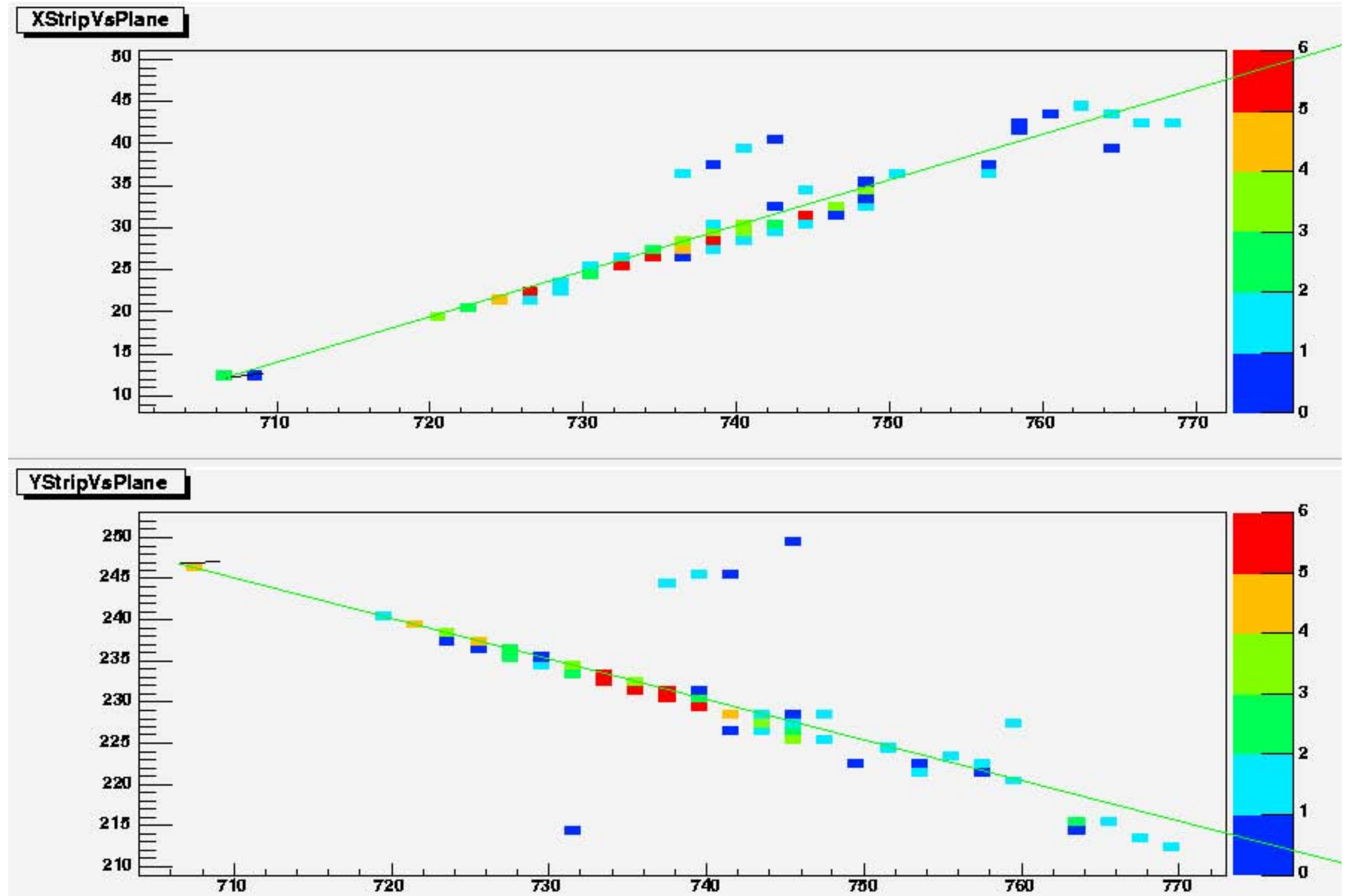
Electron and pion tracks reconstructed

Sample signal and background events in NOvA





Sample signal and background events in NOvA

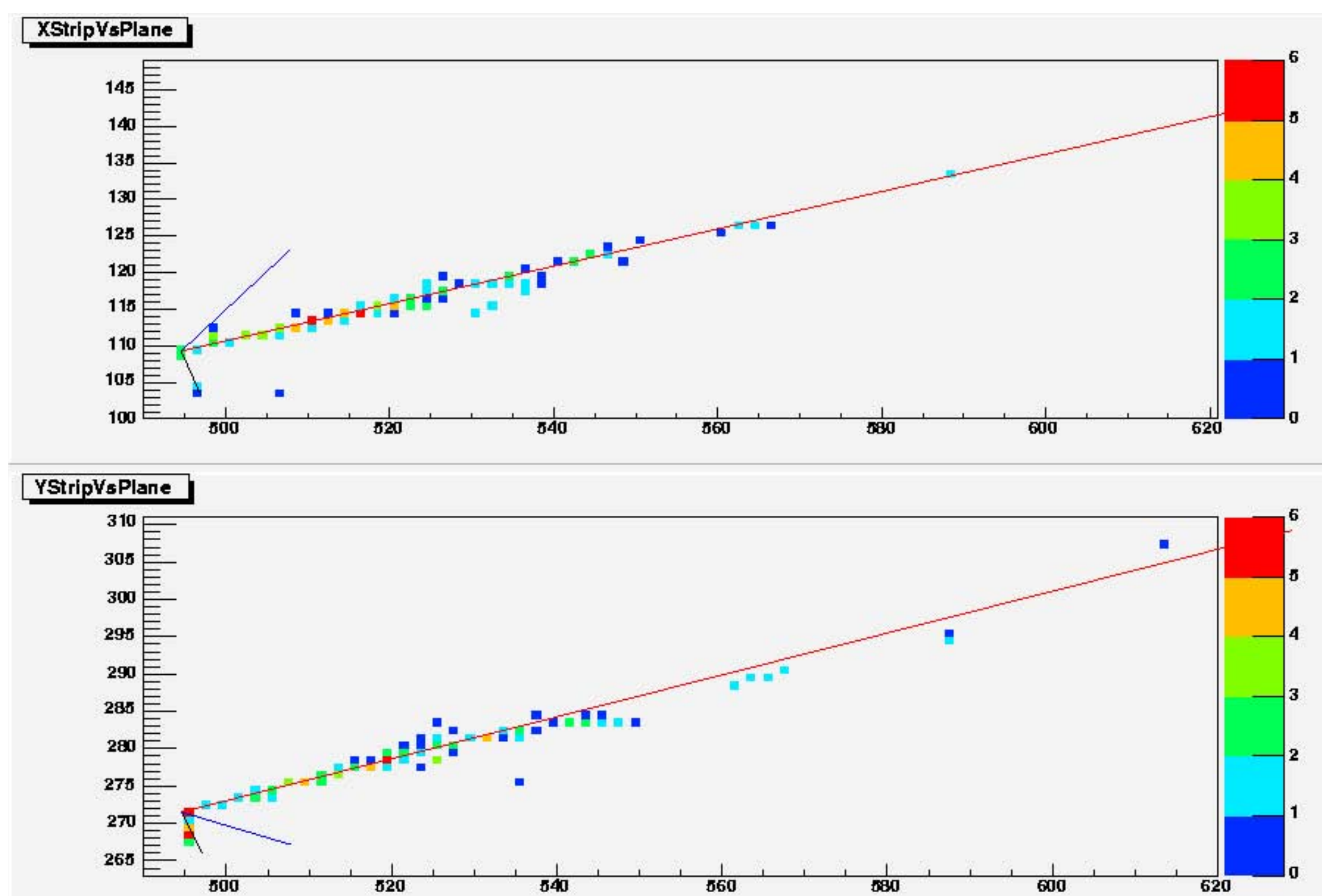


$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

E_ν=10.6 GeV

E_p=1.04GeV

$E_{\pi o}$ =1.97GeV



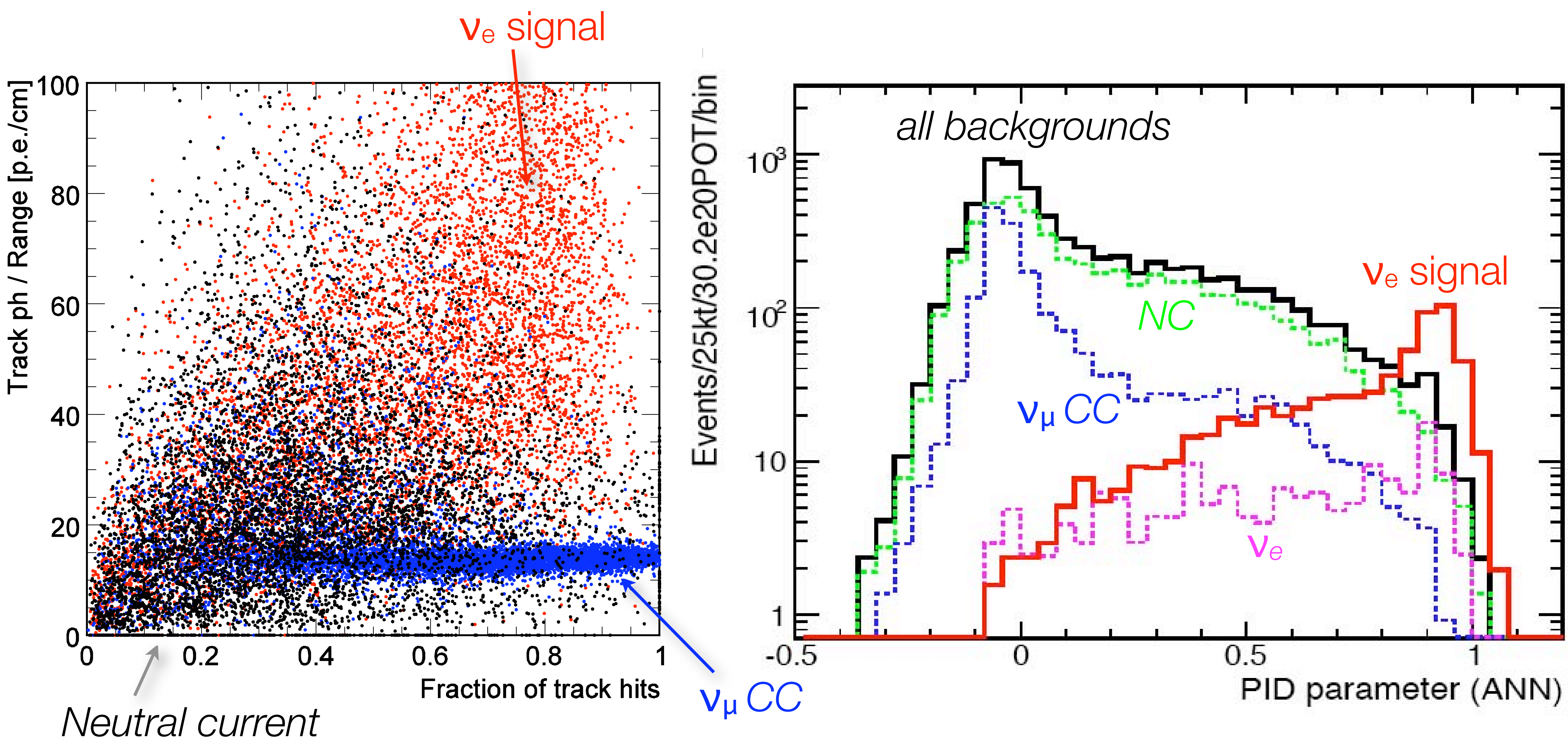
$\nu_e p \rightarrow e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

E_π=0.2GeV



Particle ID

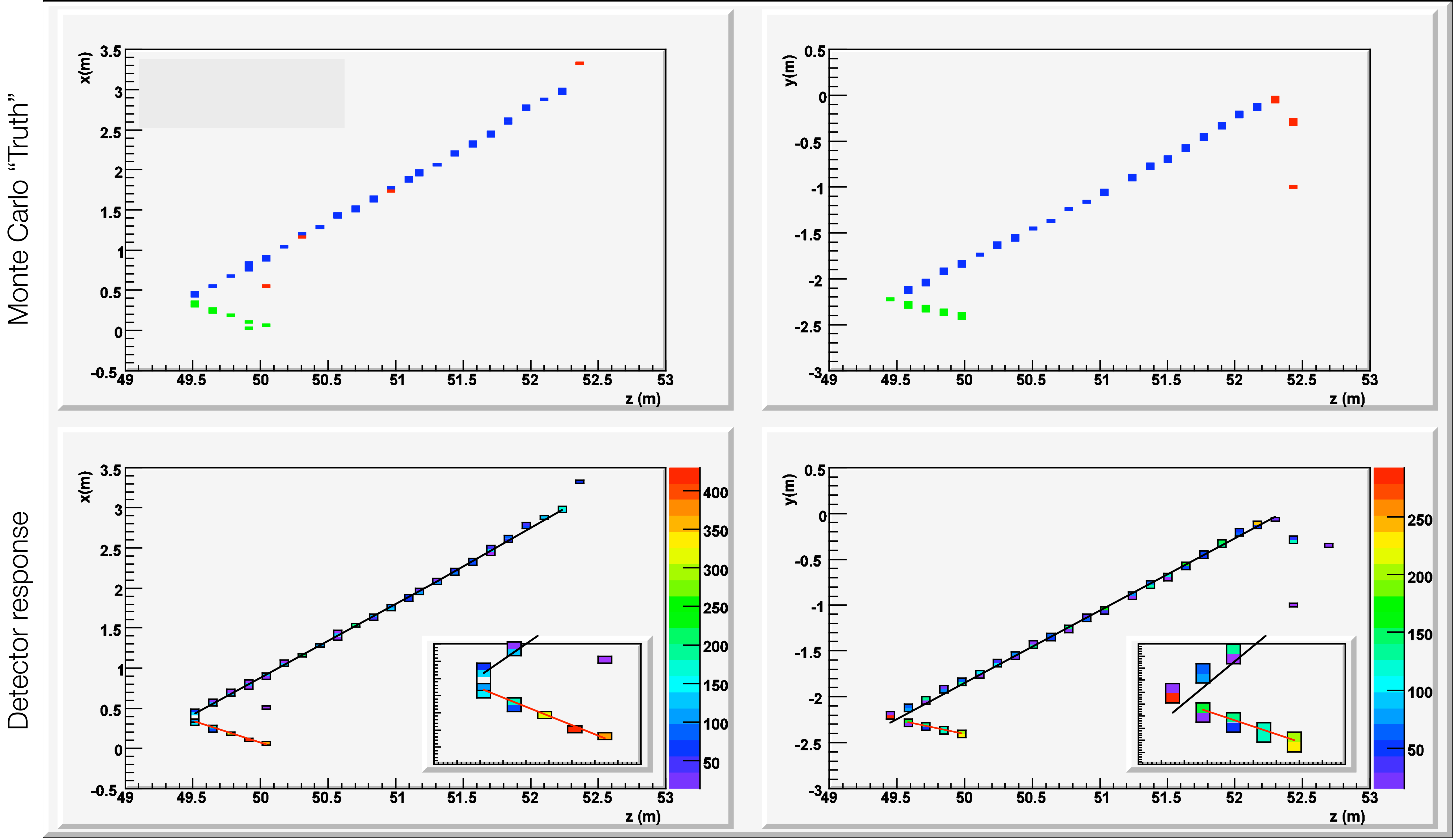
21 event shape variables input to artificial neural net

	Neutrino Running	Antinetrino Running	Total	Efficiency (Includes fiducial cut)
ν_e signal	75.0	29.0	104	36%
Backgrounds:	14.4	7.6	22	
ν_μ NC	6.0	3.6	9.6	0.23%
ν_μ CC	0.05	0.48	0.53	0.004%
Beam ν_e	8.4	3.4	11.8	14%
FOM	19.8	10.5	22.1	

Numbers generated assuming:
$\sin^2(2\theta_{13}) = 0.10$, $\sin^2(2\theta_{23}) = 1.0$, and $\Delta m_{32}^2 = 0.0024\ eV^2$

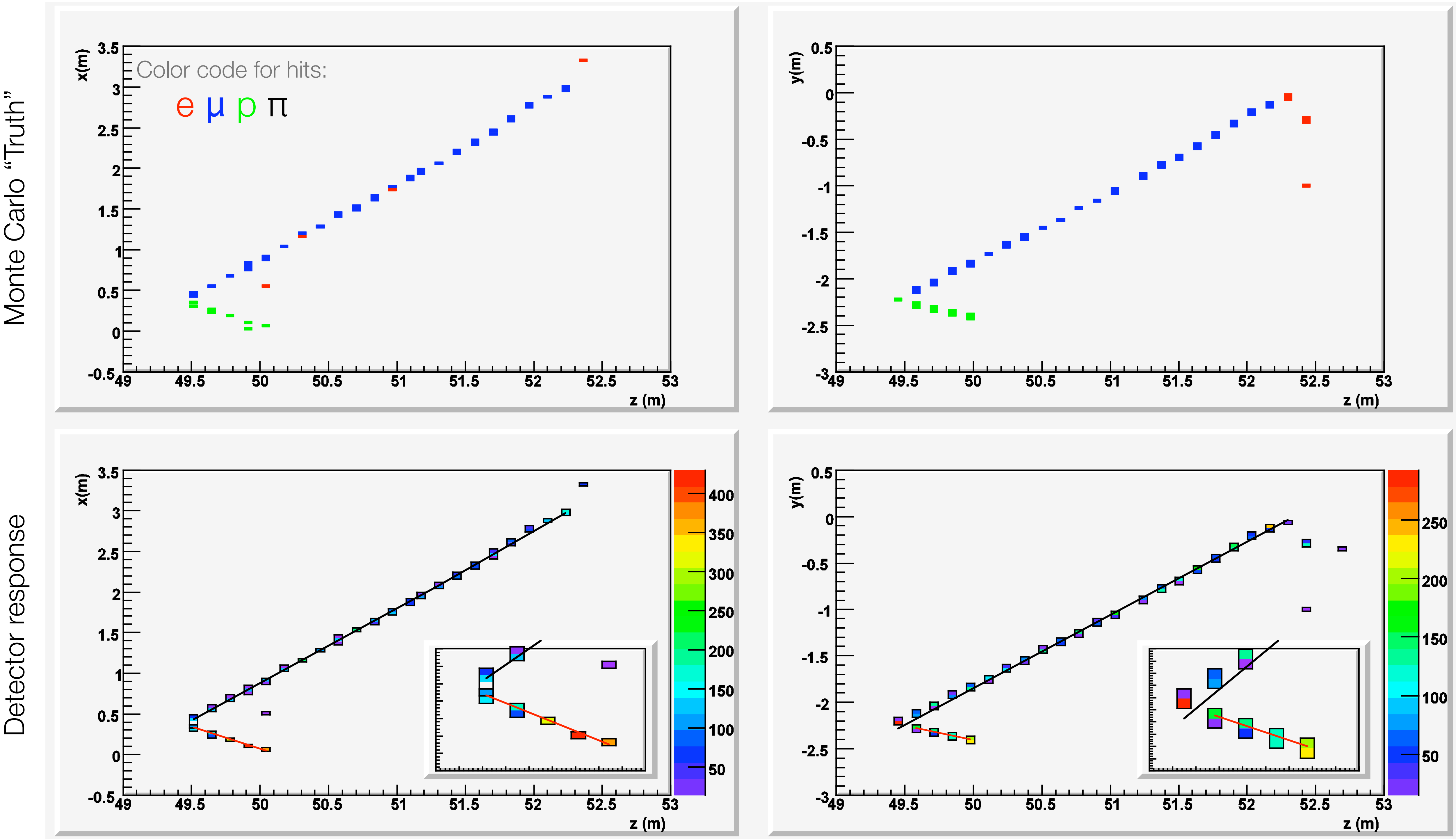
Optimizing event selection

Calculations based on $\sin^2 2\theta_{13}=0.1$ with matter effects turned off. 2 GeV NBB beam.



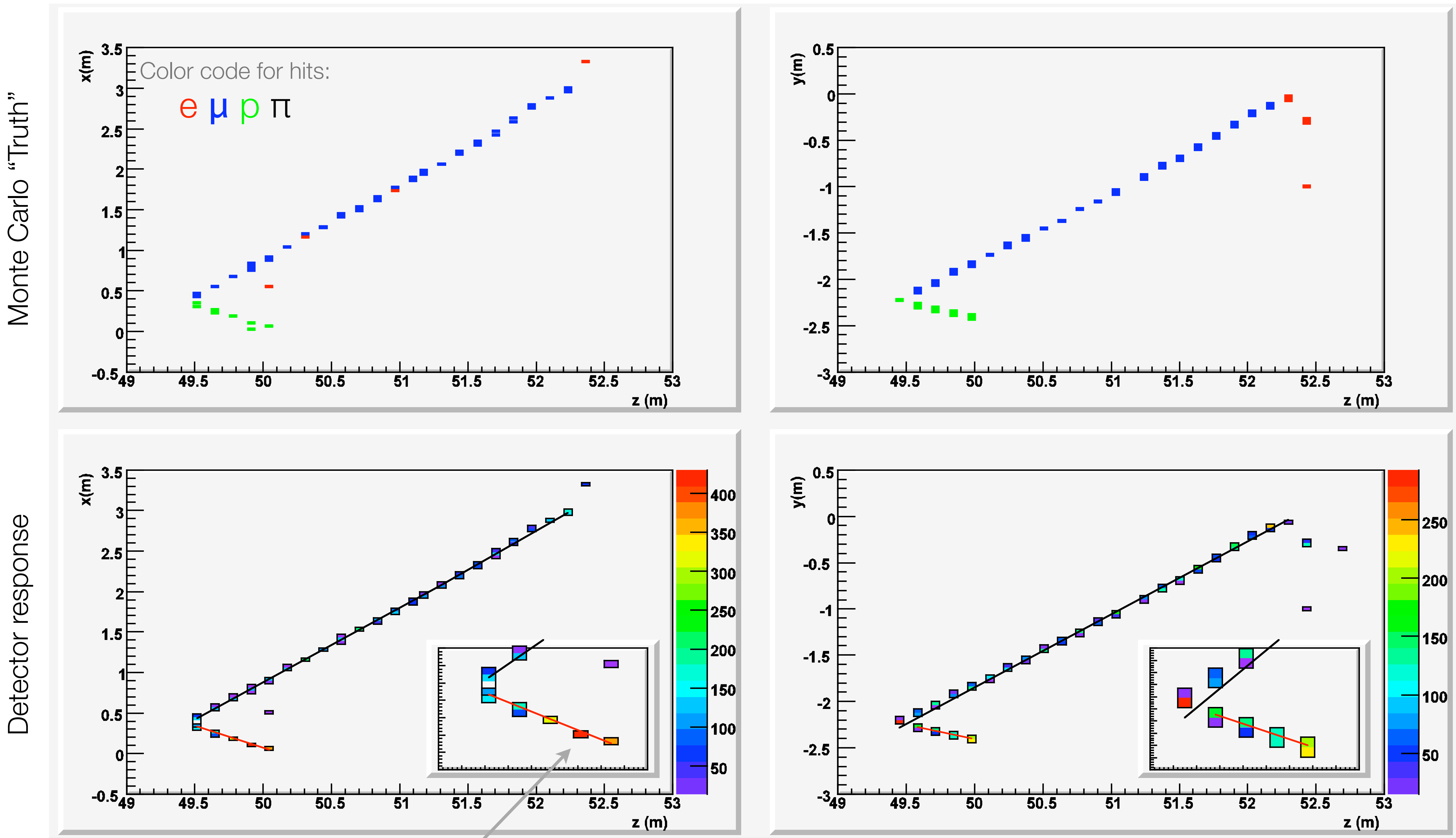
Monte Carlo “Truth”
Detector response
x(m)
y(m)
z (m)

ν_μ (1.4 GeV) + N$\rightarrow\mu^-$ (1.0 GeV) + X (QEL)



ν_μ Quasi-Elastic Event

ν_μ (1.4 GeV) + N→μ^- (1.0 GeV) + X (QEL)

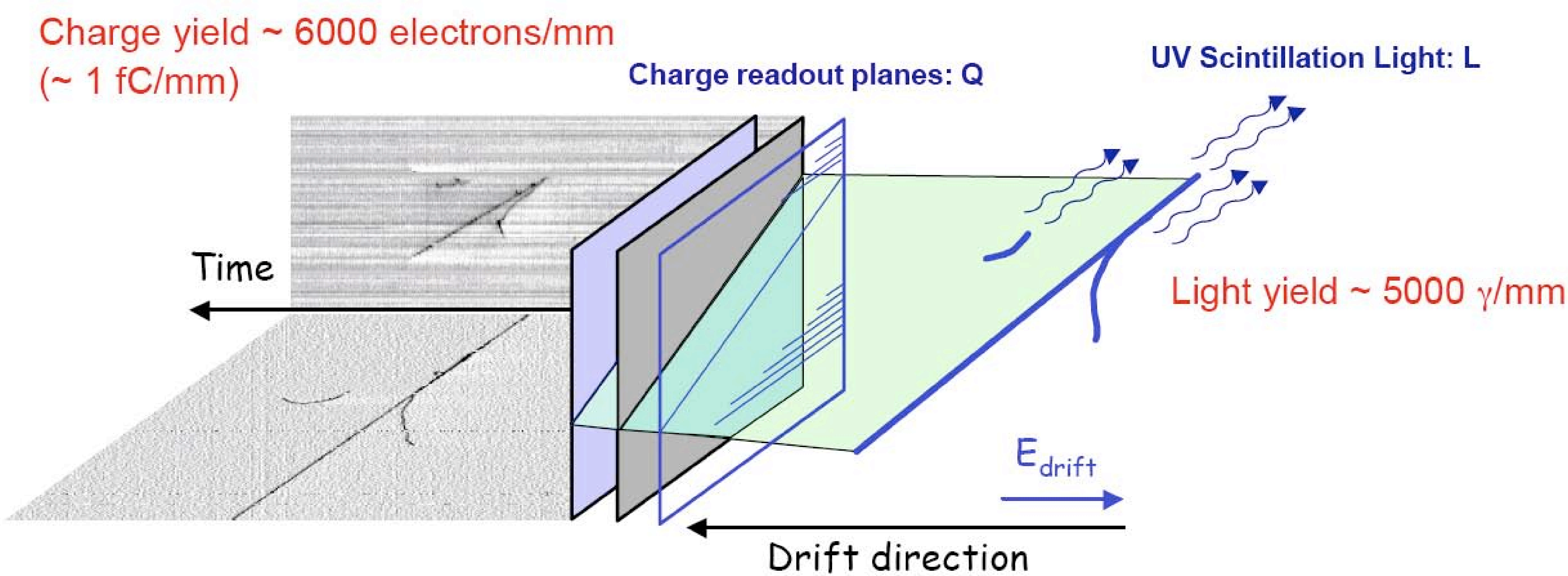


Proton ID from dE/dx

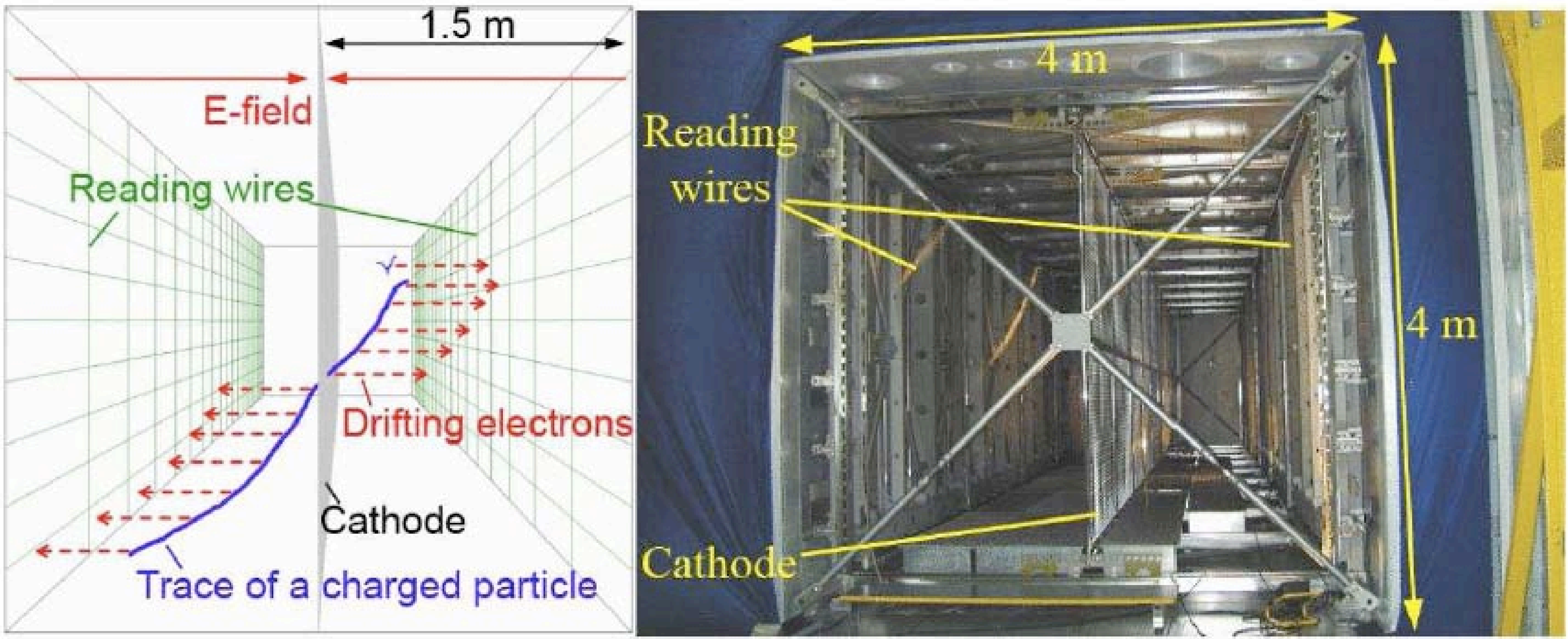
ν_μ Quasi-Elastic Event

Liquid Argon Time Projection Chamber

Liquid Argon TPC: Concept



The ICARUS LqAr Detector

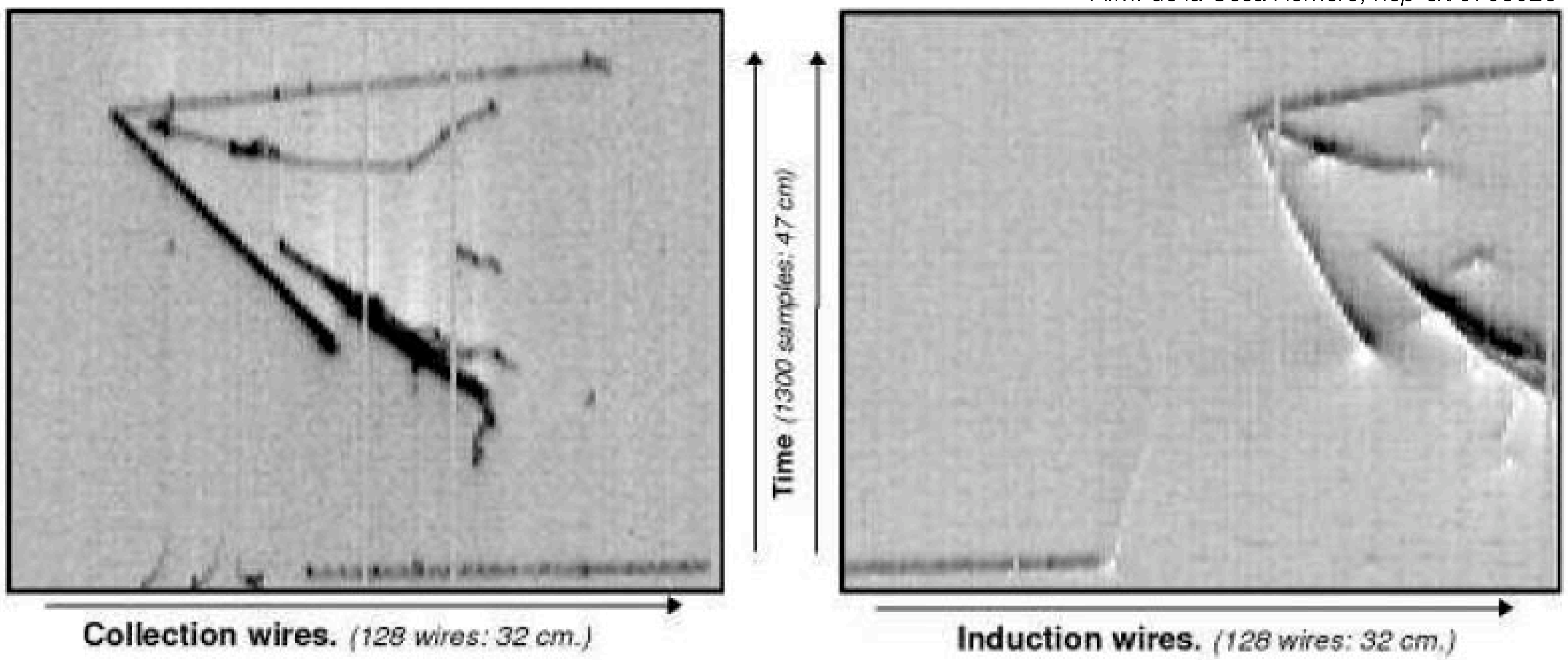


A.M. de la Ossa Romero, hep-ex/0703026

Figure 2.4: Picture of the open T300 ICARUS module during assembly.

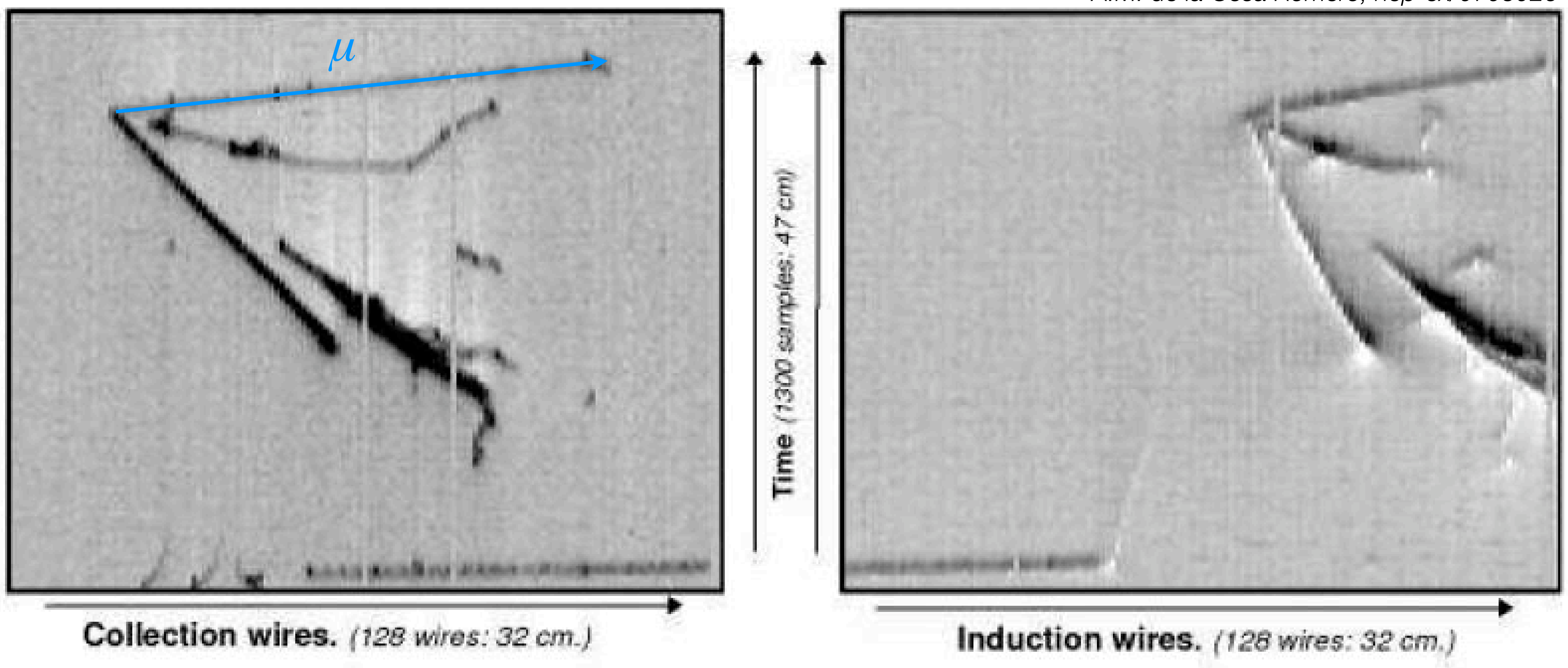
What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



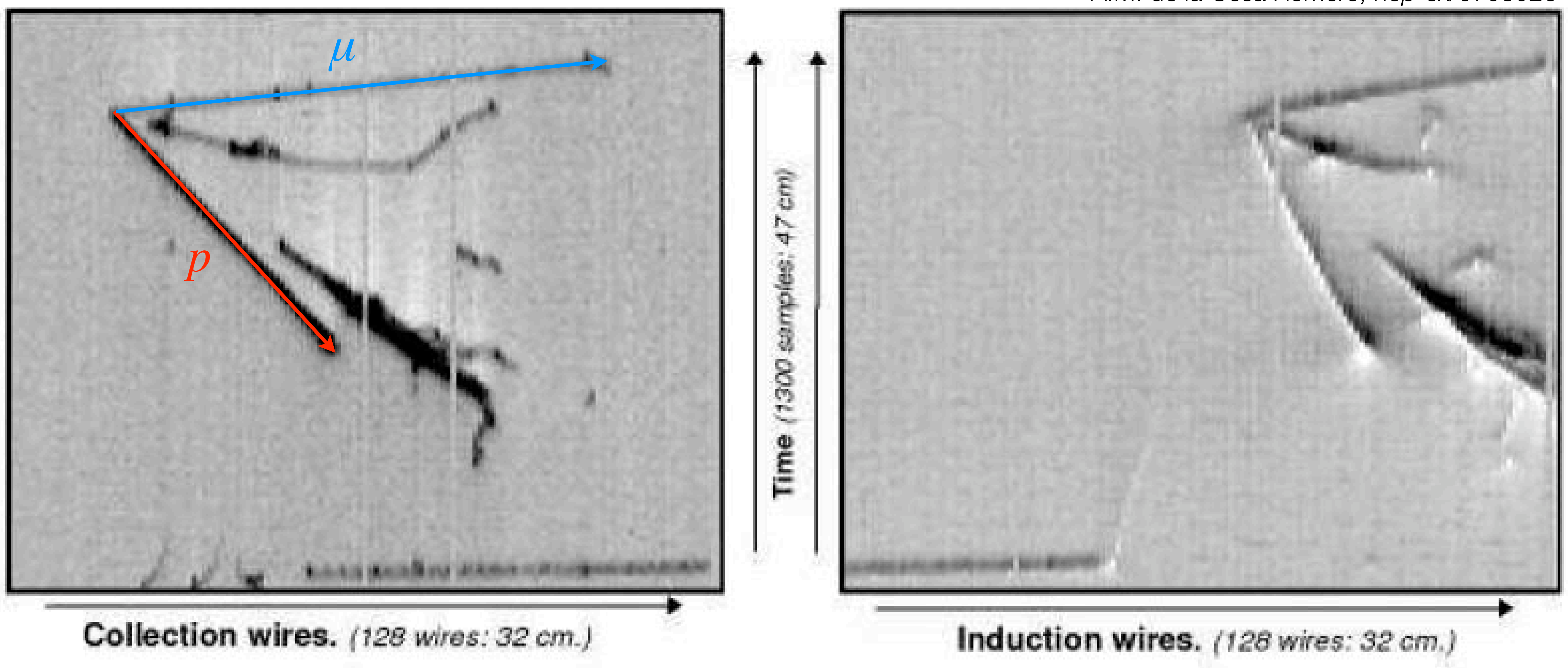
What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



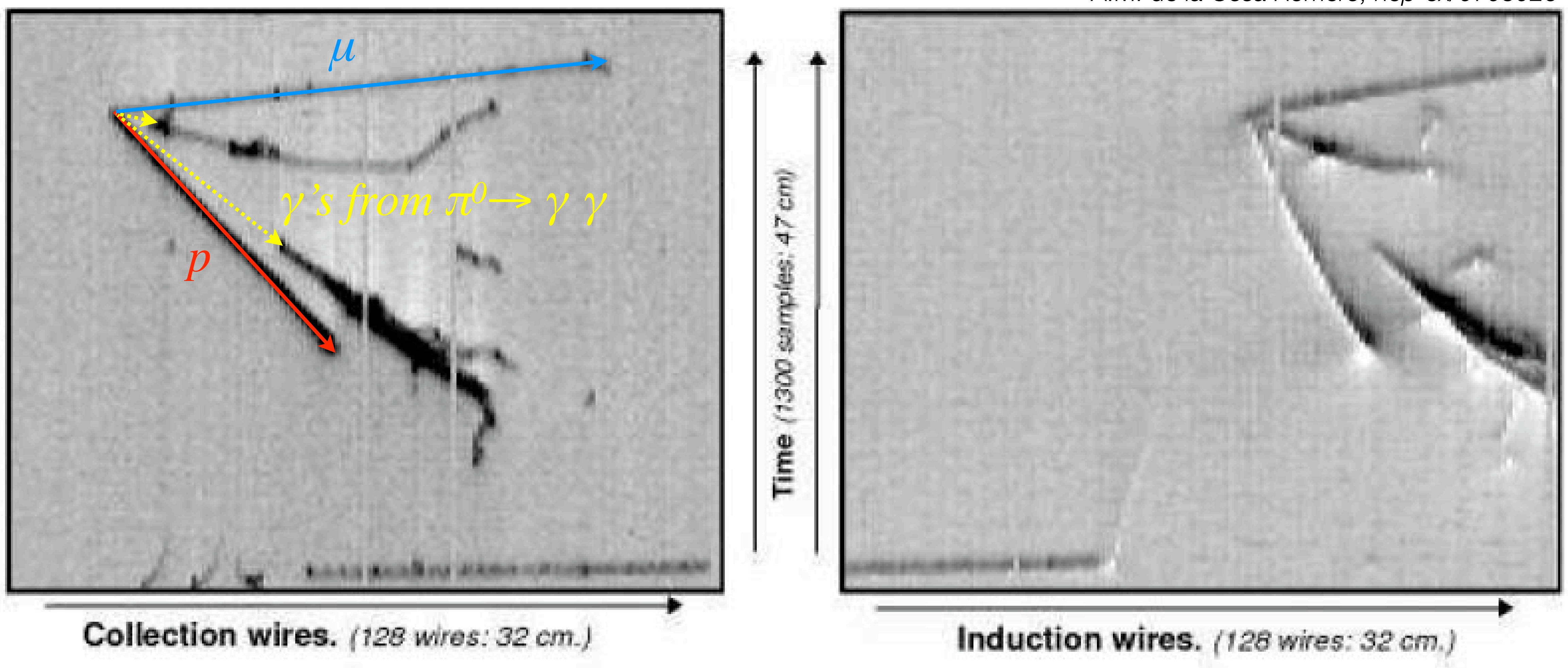
What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026

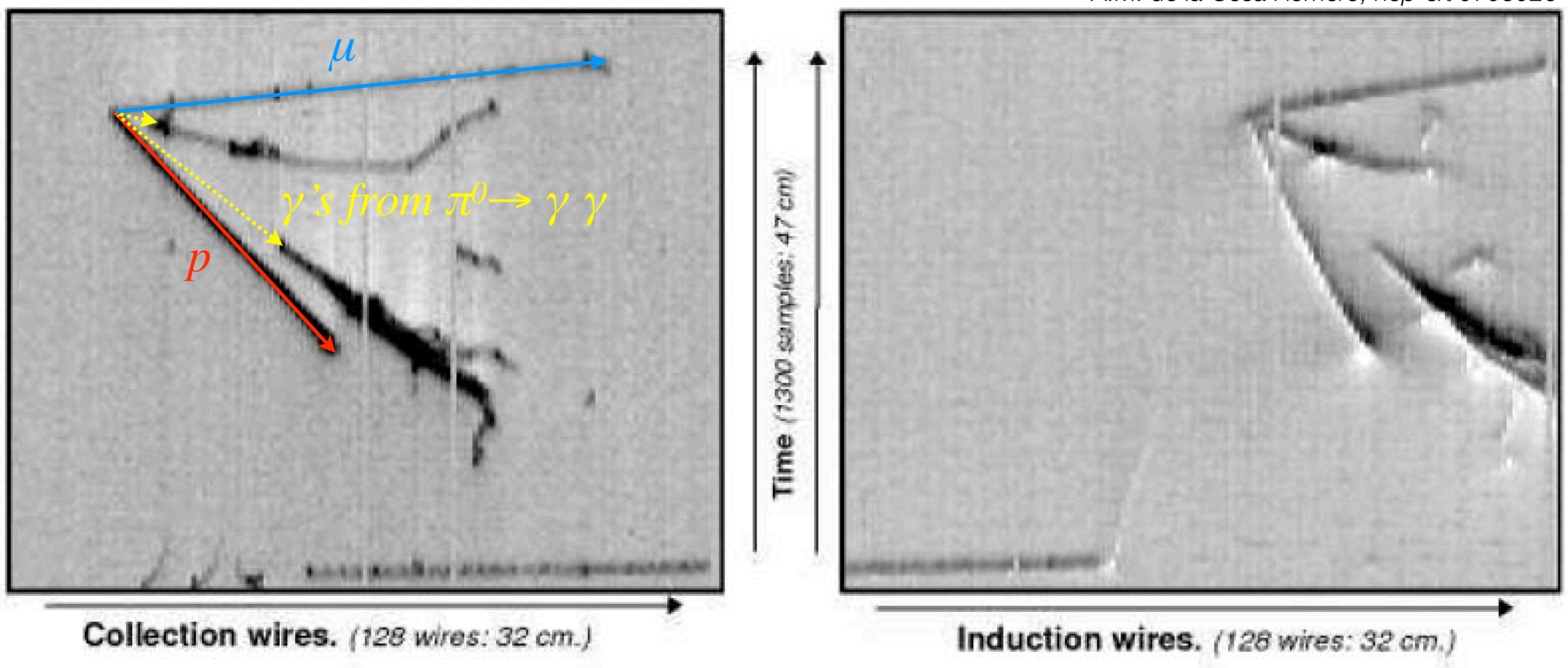
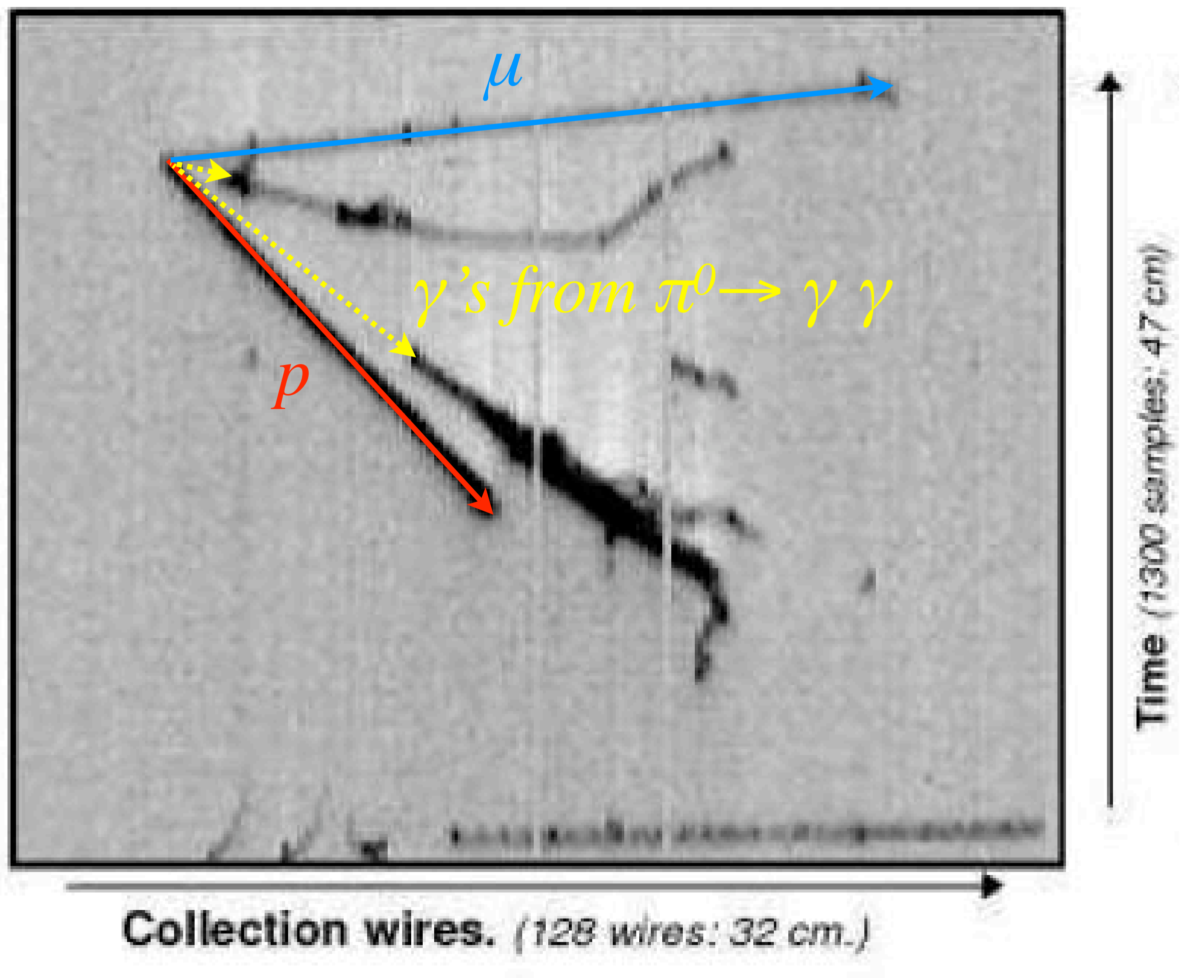


Figure 5.21: The raw image of a low multiplicity real event in the collection (left) and induction plane (right). The event is reconstructed as ($\nu_\mu\ n \rightarrow \mu^- \Delta^+ \rightarrow \mu^-\ p\ \pi^0$) with a mip leaving the chamber, an identified stopping proton and a pair of converted photons from the π^0 decay. When these photons escape from the chamber, the event is tagged as a *golden* event.

What's going on in this event?

Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



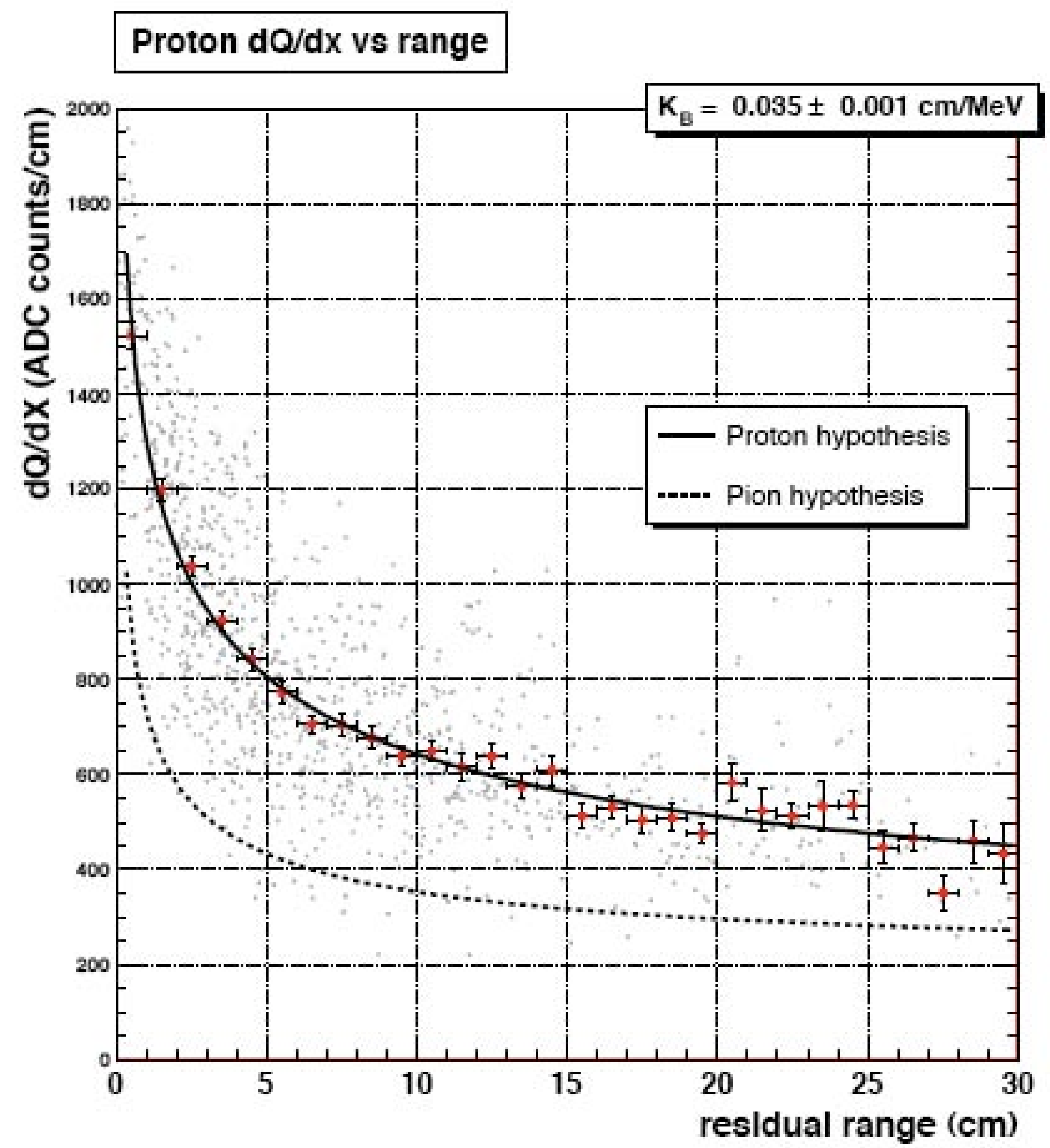
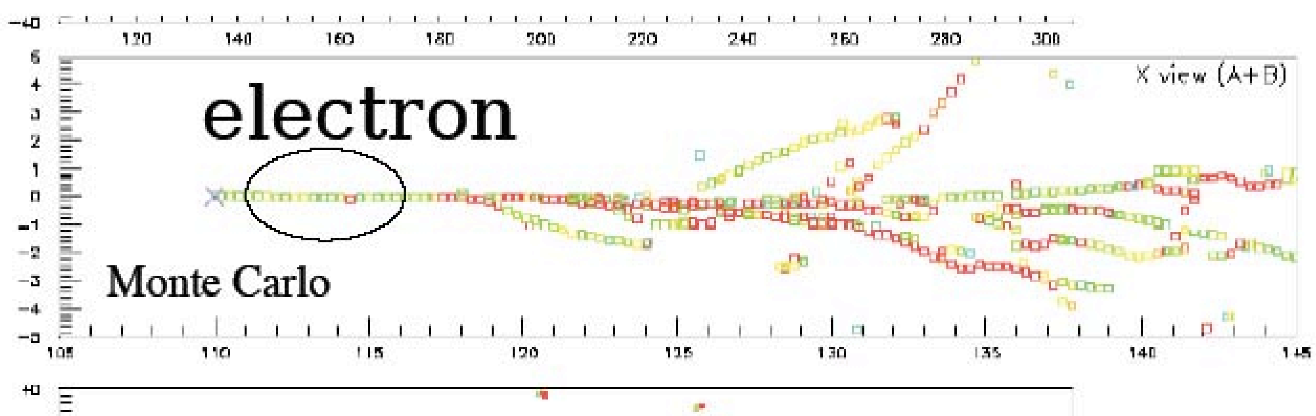
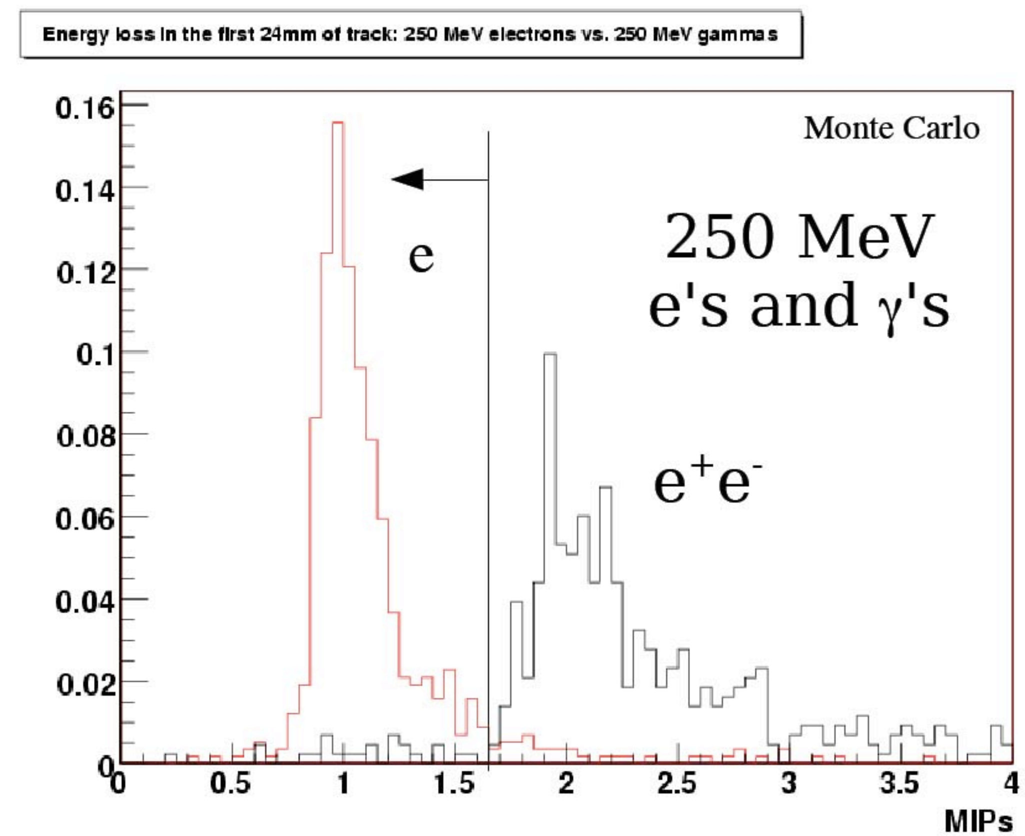


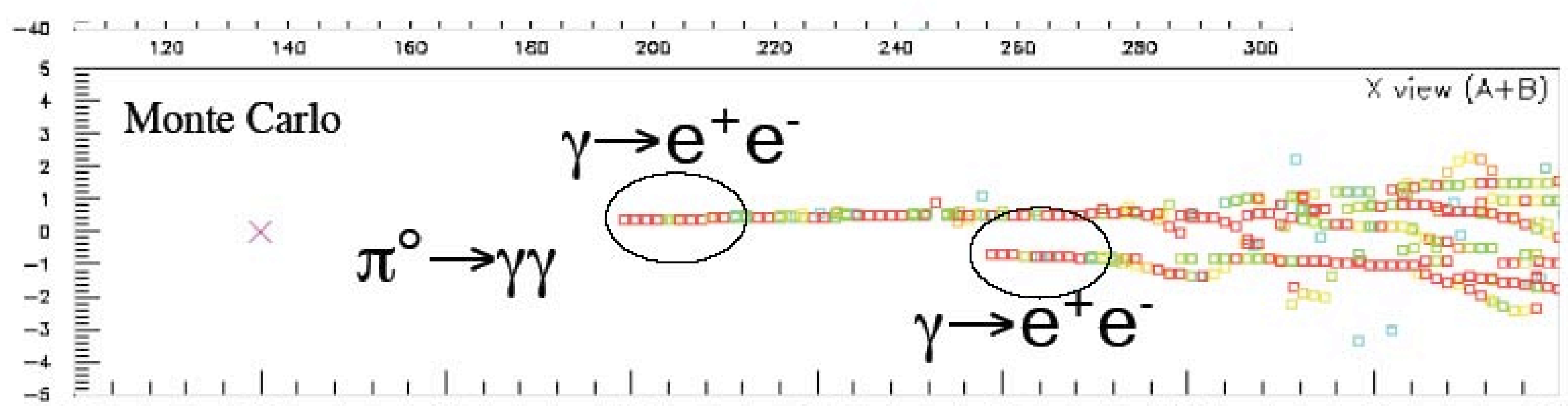
Figure 5.21: The raw image of a low multiplicity ... on plane (right). The event is reconstructed as (ν_μ ... ne chamber, an identified stopping proton and a pair ... en these photons escape from the chamber, the event is tagged as a *golden* event.

Electron / Photon Separation

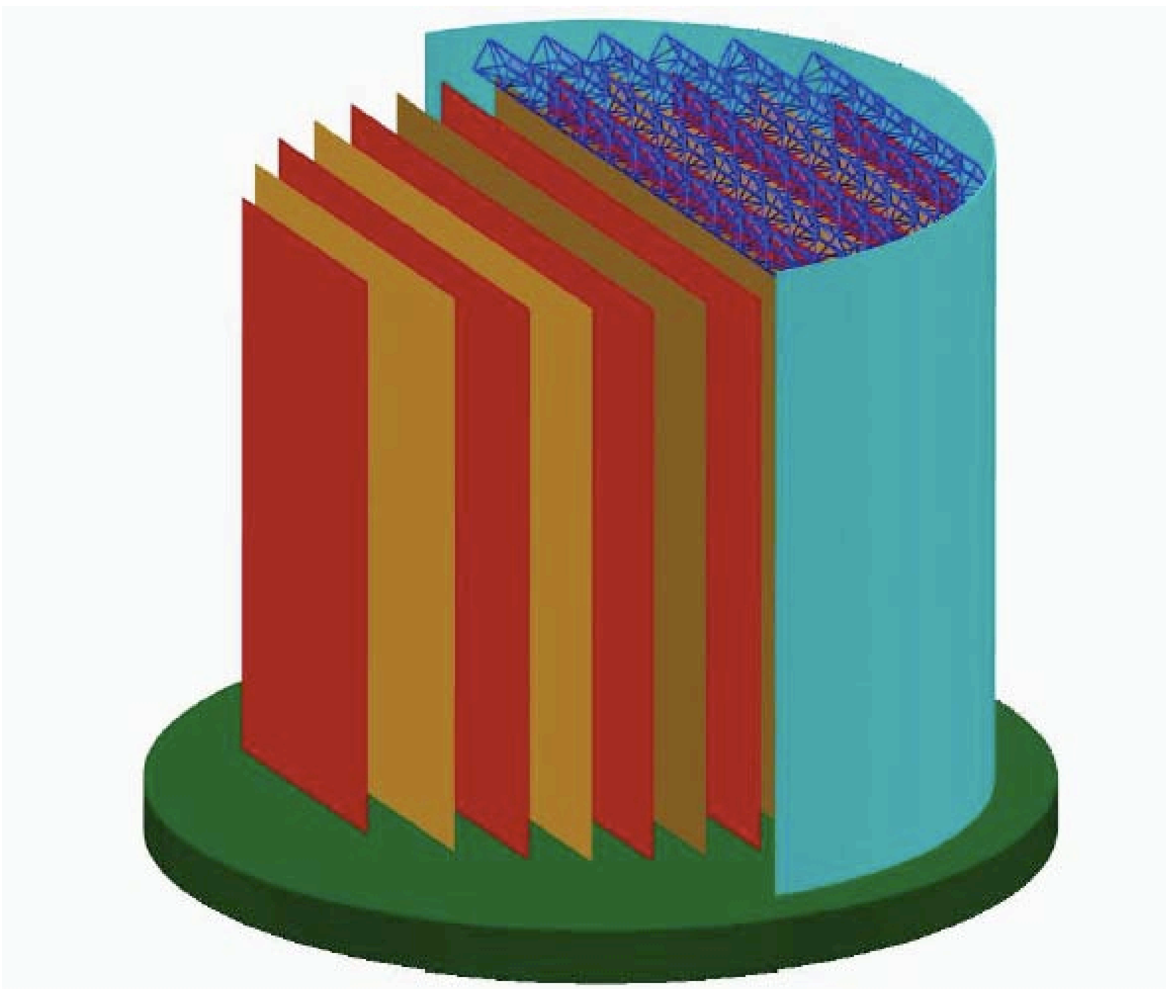
Check dE/dx at start of shower



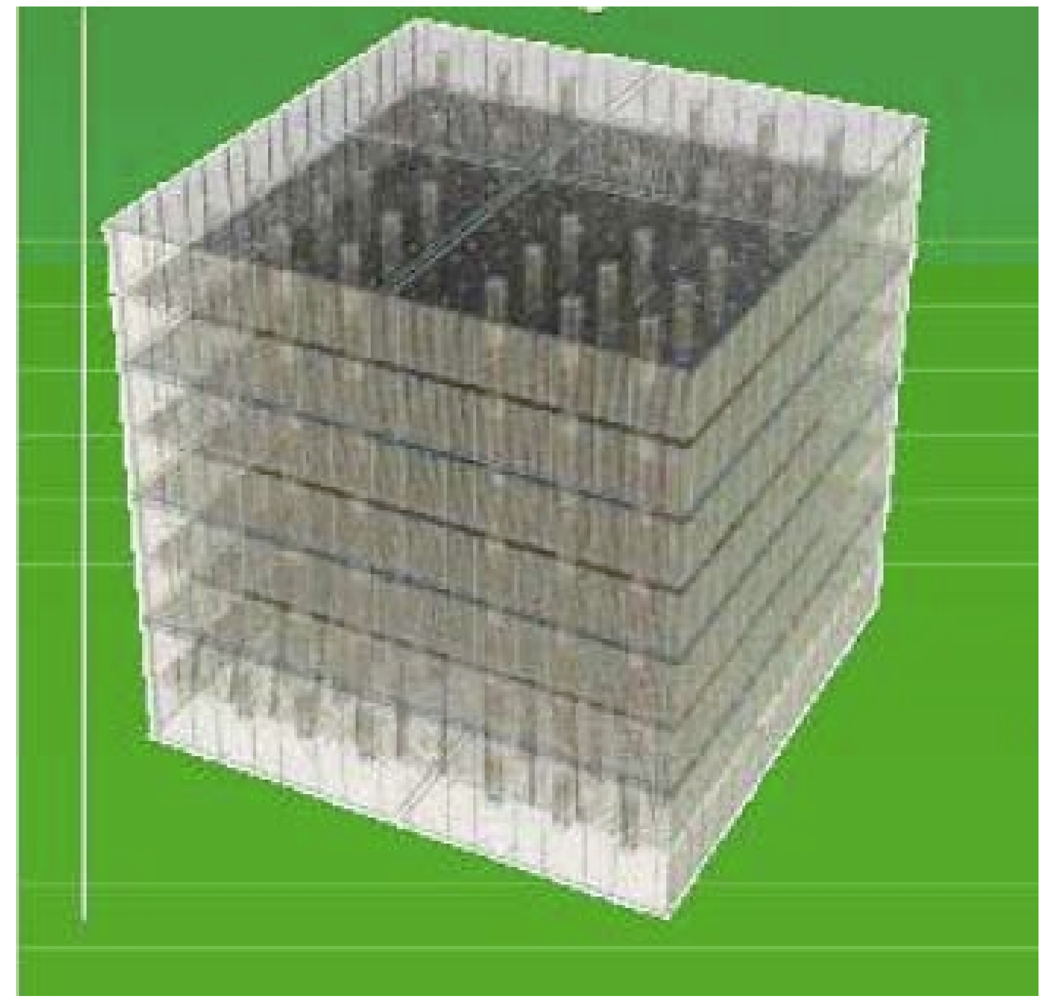




Some possible designs for big detectors

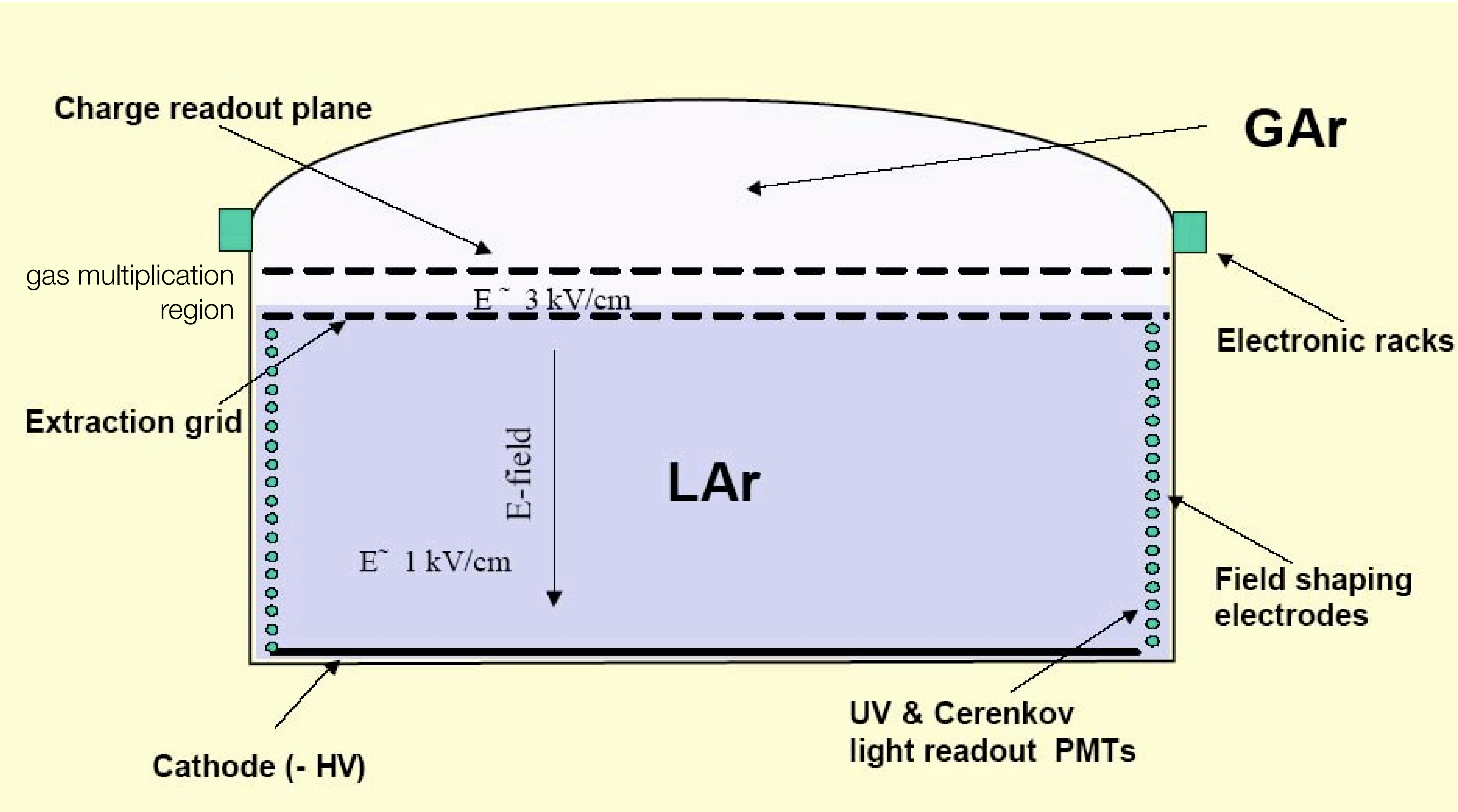


LArTPC: 10-50 kton storage tank. Modular drift regions.



LANDD: Single vessel designed to support vacuum

GLACIER Concept

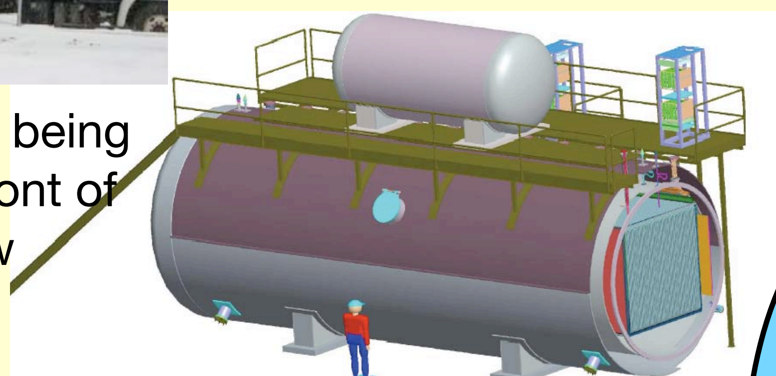


In gas multiplication region, electrons shower in a region of high electric field. Energy/ particle goes up as a result of acceleration in the field.

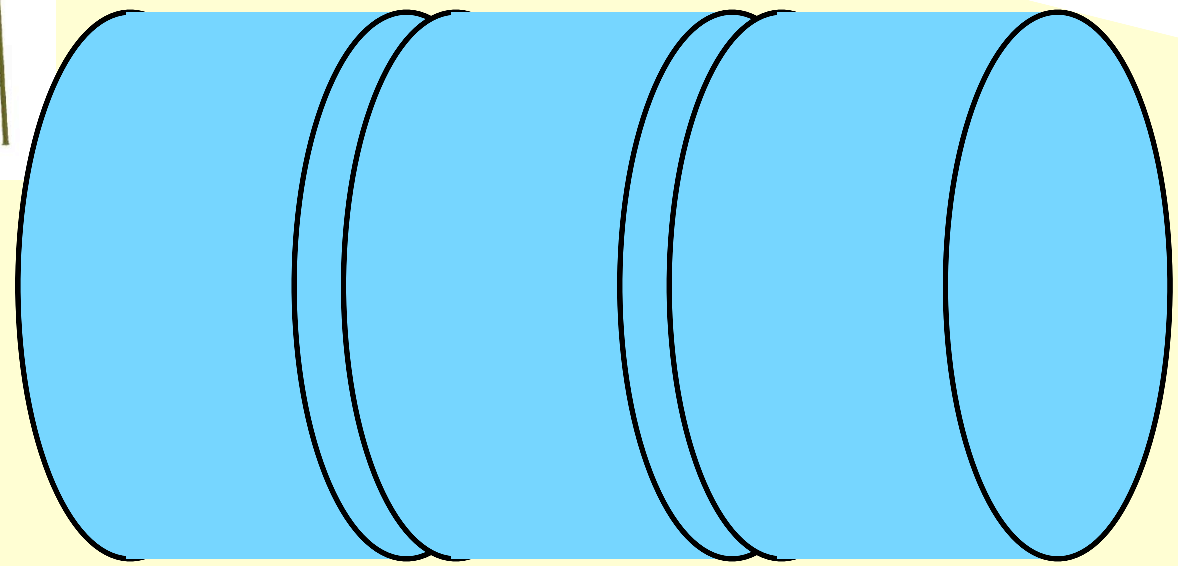
Path to large detectors (U.S.)

0.3 ton → *x600* → *170 ton* → *x30* → *5 kton* → *x20* → *100 kton*

"ArgoNeut" being placed in front of MINOS now



"MicroBooNE" in 8 GeV beamline at Fermilab



LAr5 in NuMI or future DUSEL beamline

?

Eventual goal: 100 kt

R&D issues

- Are the drift distances required by large detectors achievable in large cryostats?
- Electronic optimization. Multiplexing? Noise?
- Large wire plane construction

Tau neutrinos

- Tau neutrinos are difficult to observe
  - They are difficult to produce. First direct observation (DONUT) was via decays of charmed particles in a beam dump.
  - They are difficult to make interact: Threshold for tau production is 3.5 GeV. This puts them above the oscillation maximum for most beams designed to study oscillations at the atmospheric mass-squared scale. For example, for L=735 km, Emax = 1.5 GeV, which is below threshold
  - They are difficult to detect: The lifetime of the tau is 291 fs; Even when highly boosted, decay length is only a few mm. Required a very finely segmented vertex region
- Tau neutrinos produce backgrounds to electron neutrino searches:

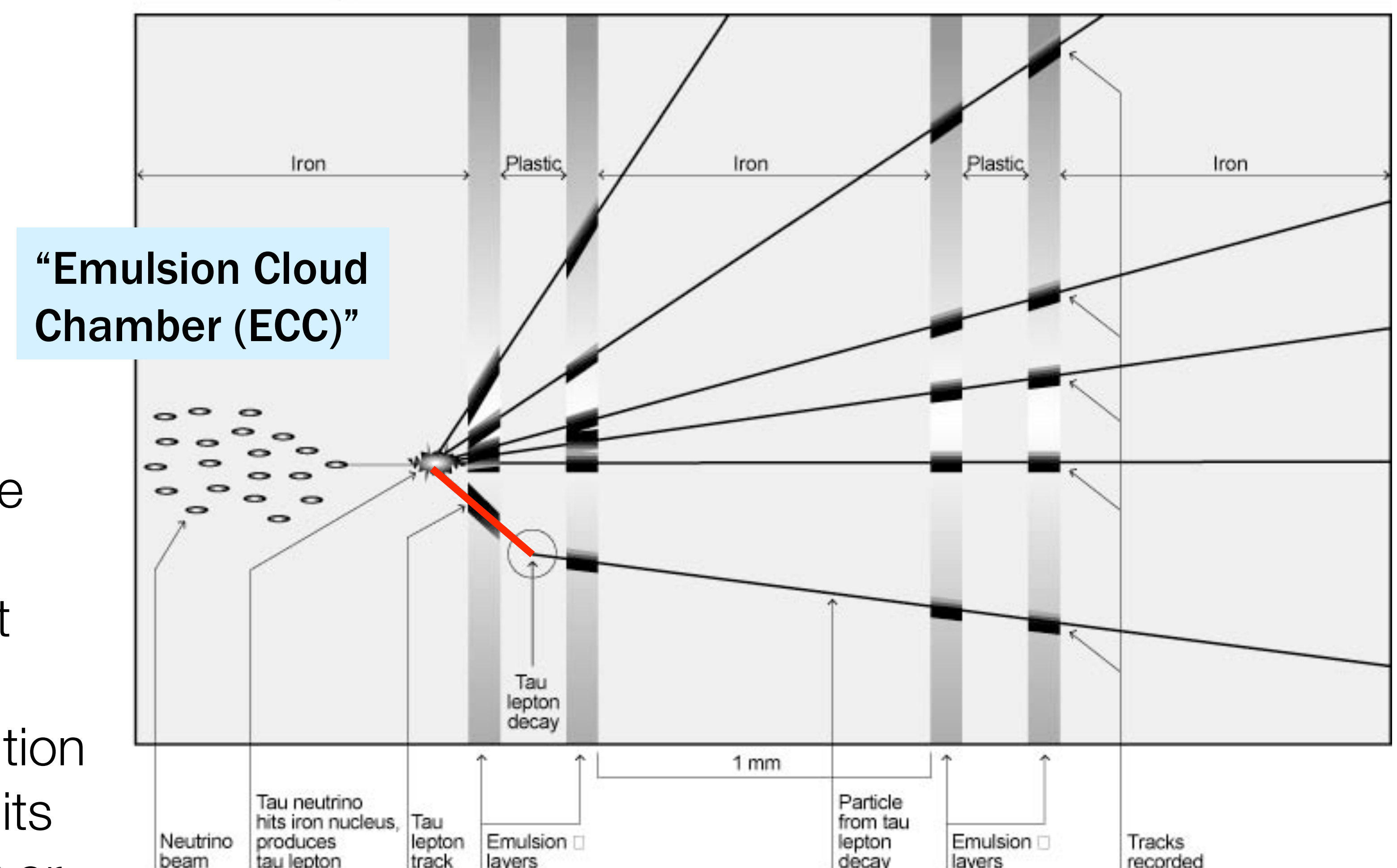
$$\tau \longrightarrow e \ \nu_e \ \nu_\tau$$

Tau Neutrino Detection

- Several experiments look for tau neutrinos
- Observed by DONUT experiment
- Sought from oscillations by CHORUS and OPERA

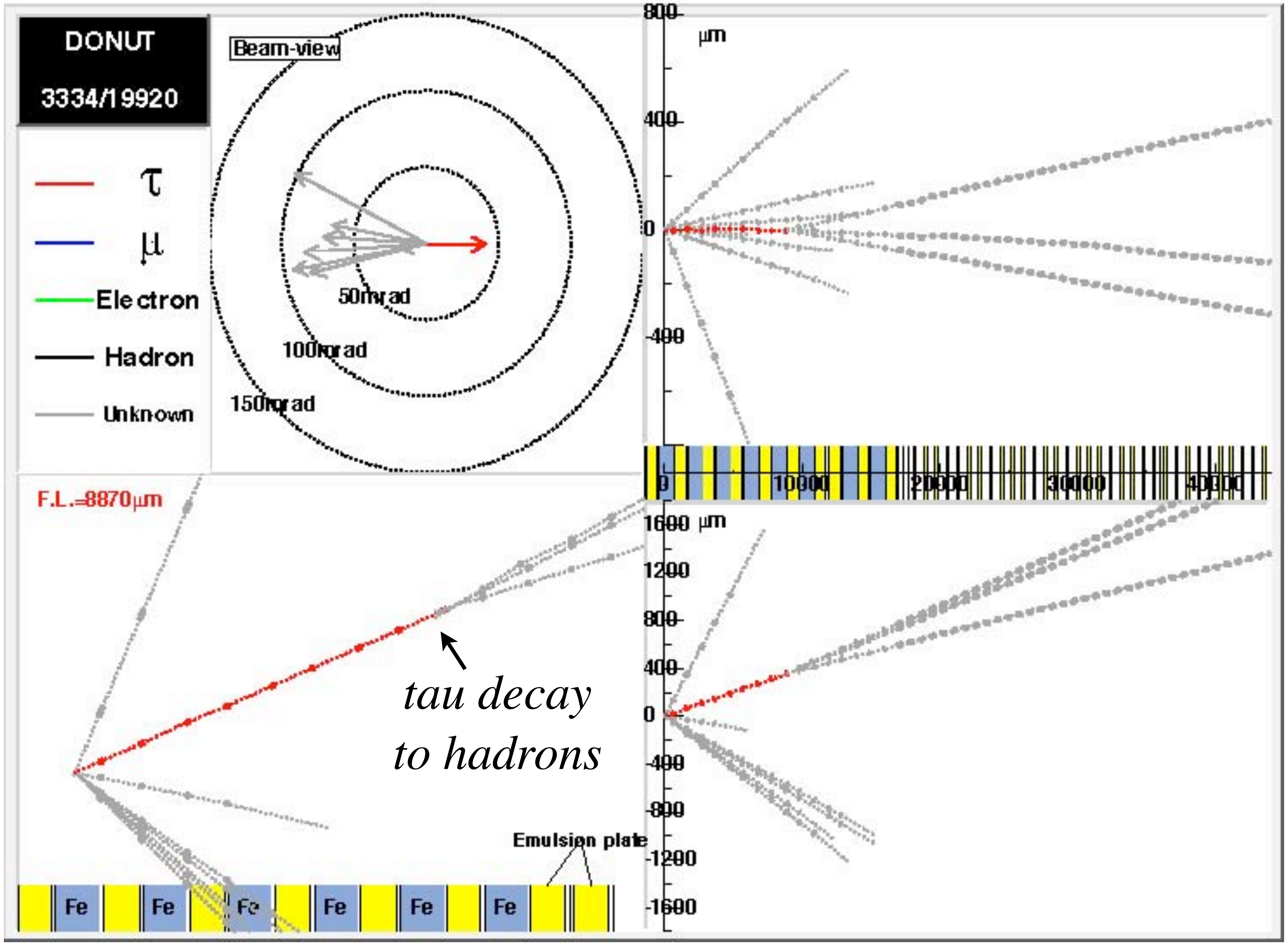
- All of the above experiments have used thin films of photographic emulsions placed between target layers
- Use of emulsion allows for resolution of short tau track and search for its decay either through a track kink or to multi-prongs
- Emulsion target followed by other detectors which provide tracking and tell you where you had a neutrino interaction and which emulsions you should develop

Detecting a Tau Neutrino



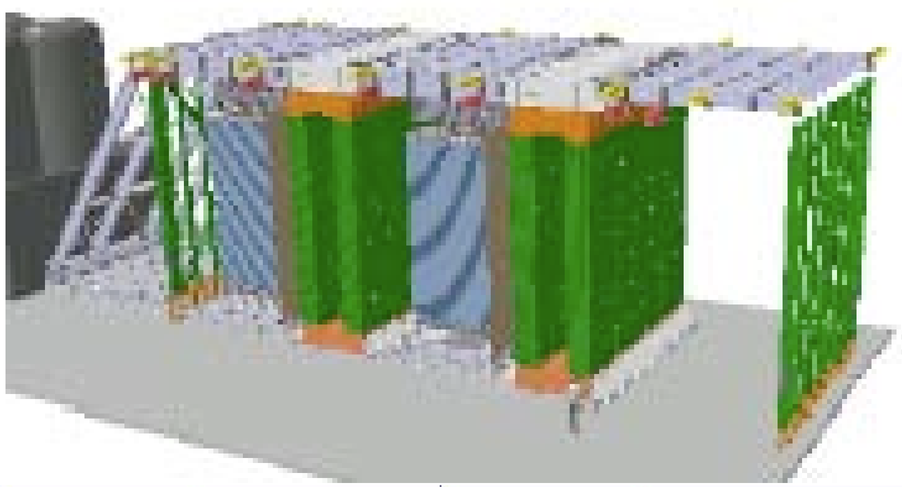
Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Tau Neutrino Detection by DONUT Collaboration



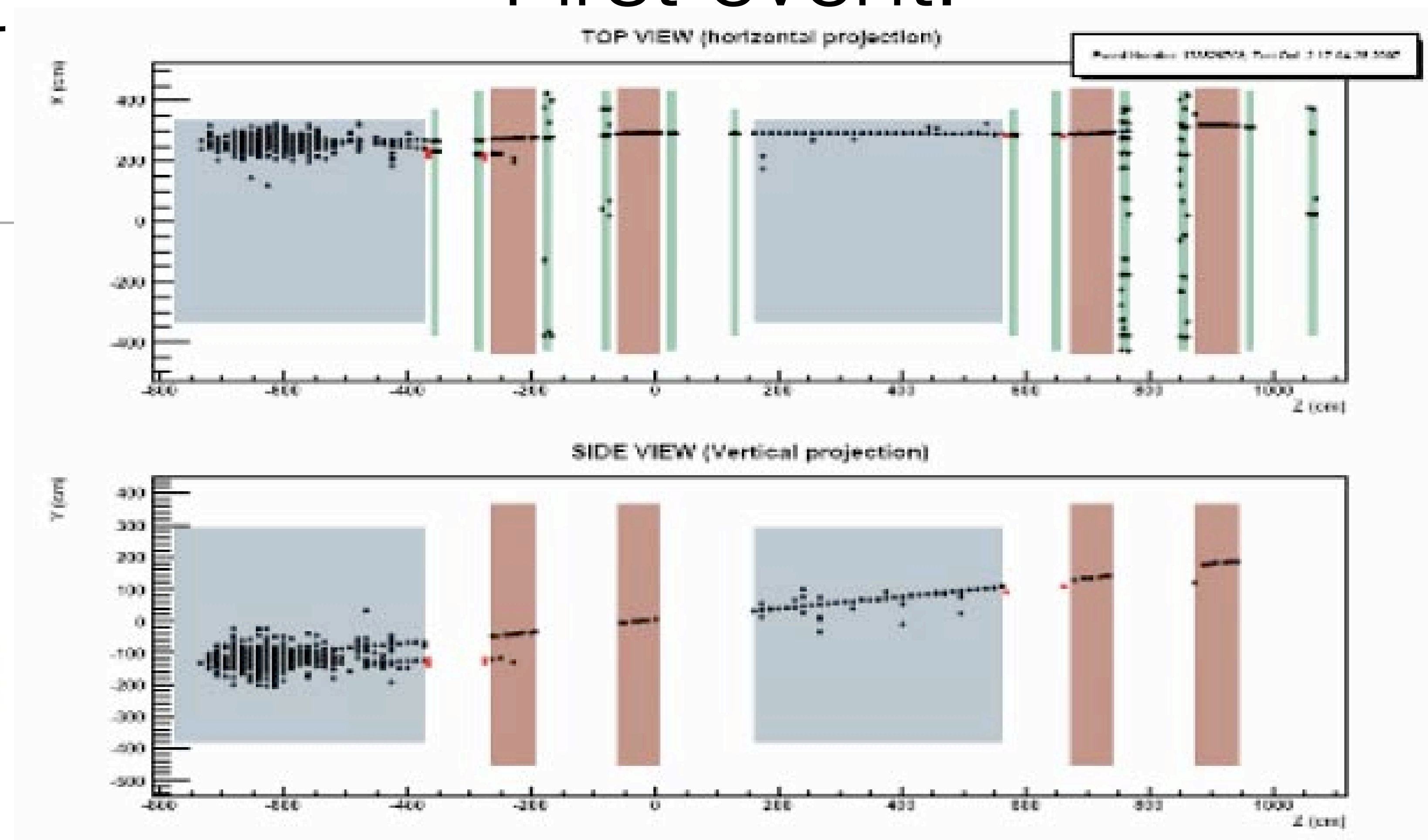
OPERA Experiment In CNGS beam

OPERA uses bricks of lead/emulsion embedded in a solid scintillator-based tracking system + downstream muon spectrometer

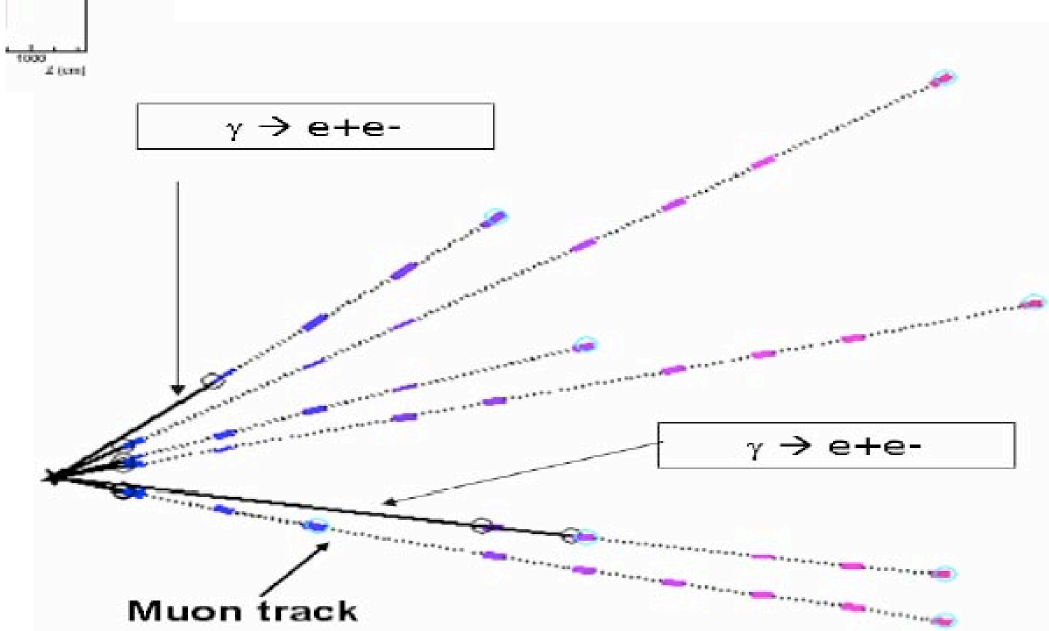


τ^- decay channels	Signal ÷ Δm^2 (Full mixing)		Background
	2.5×10^{-3} (eV^2)	3.0×10^{-3} (eV^2)	
$\tau^- \to \mu^-$	2.9	4.2	0.17
$\tau^- \to e^-$	3.5	5.0	0.17
$\tau^- \to h^-$	3.1	4.4	0.24
$\tau^- \to 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76

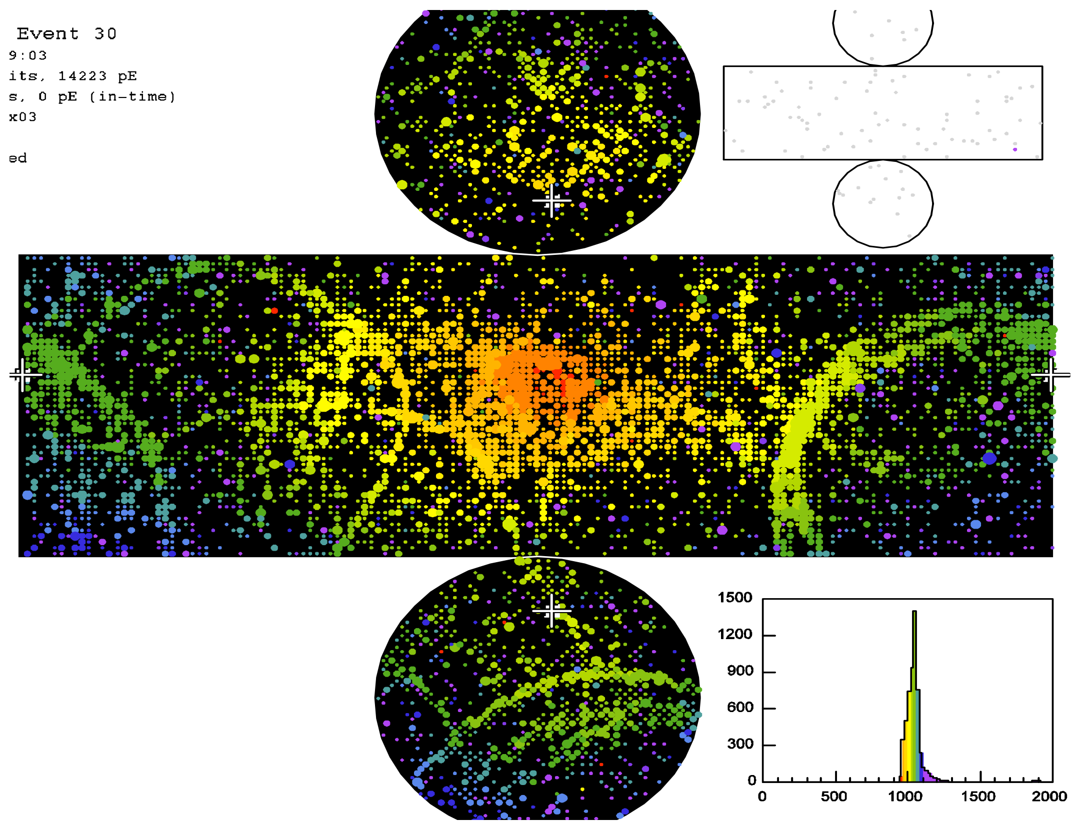
First event!



compatible $\pi 0 \to 2\gamma$:
$\pi 0$ mass: 110 ± 30 MeV



Statistical Tau Appearance



While large detectors may not to be able to identify tau neutrino events one-by-one, they may be able to separate tau neutrino events from other events statistically