Detector Basics II

Mark Messier
Indiana University

Neutrino Summer School
Fermilab, July 7th, 2009

Results of my index card survey

EXO	/ 1
CUORE	// 2
Majorana/GERDA	/// 3
SuperNEMO	//// 4
KATRIN	// 2
LVD	/ 1
KamLAND	/ 1
BOREXINO	// 2
DoubleCHOOZ	/////// 7
Daya Bay	//////// 8
Hanohano	/ 1
SNO+	// 2
MiniBooNE	// 2
MicroBooNE	// 2
MINOS	////////// 10
MINERvA	// 2
T2K/SK/MEMPHYSIS	////////// 10
NOVA	////// 6
LqAr	//// 4
Ice Cube	//// 4
Pierre Auger	/ 1

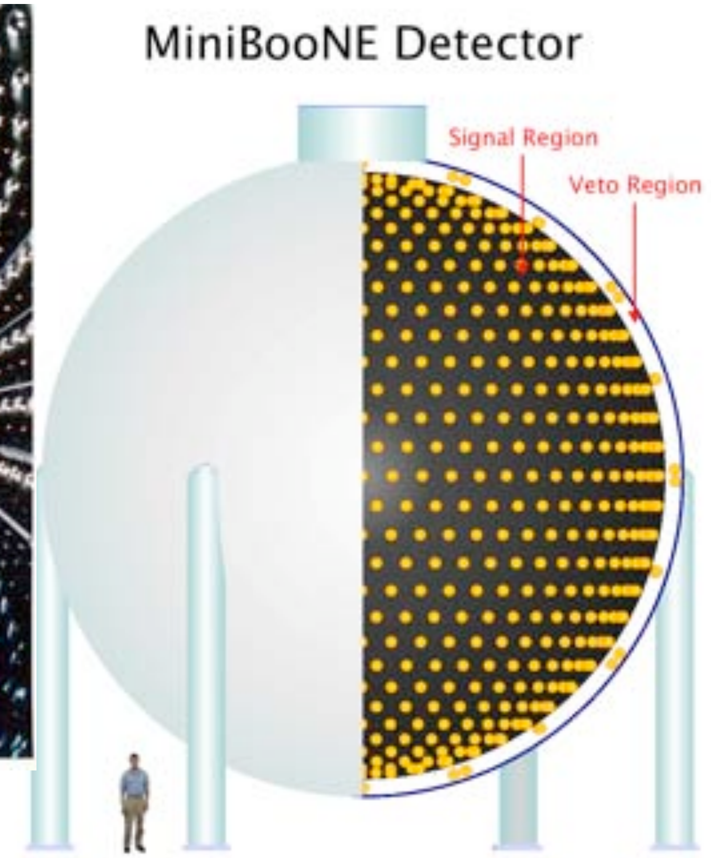
Answers to questions posted at:
http://enrico1.physics.indiana.edu/messier/post/nss09qanda.txt

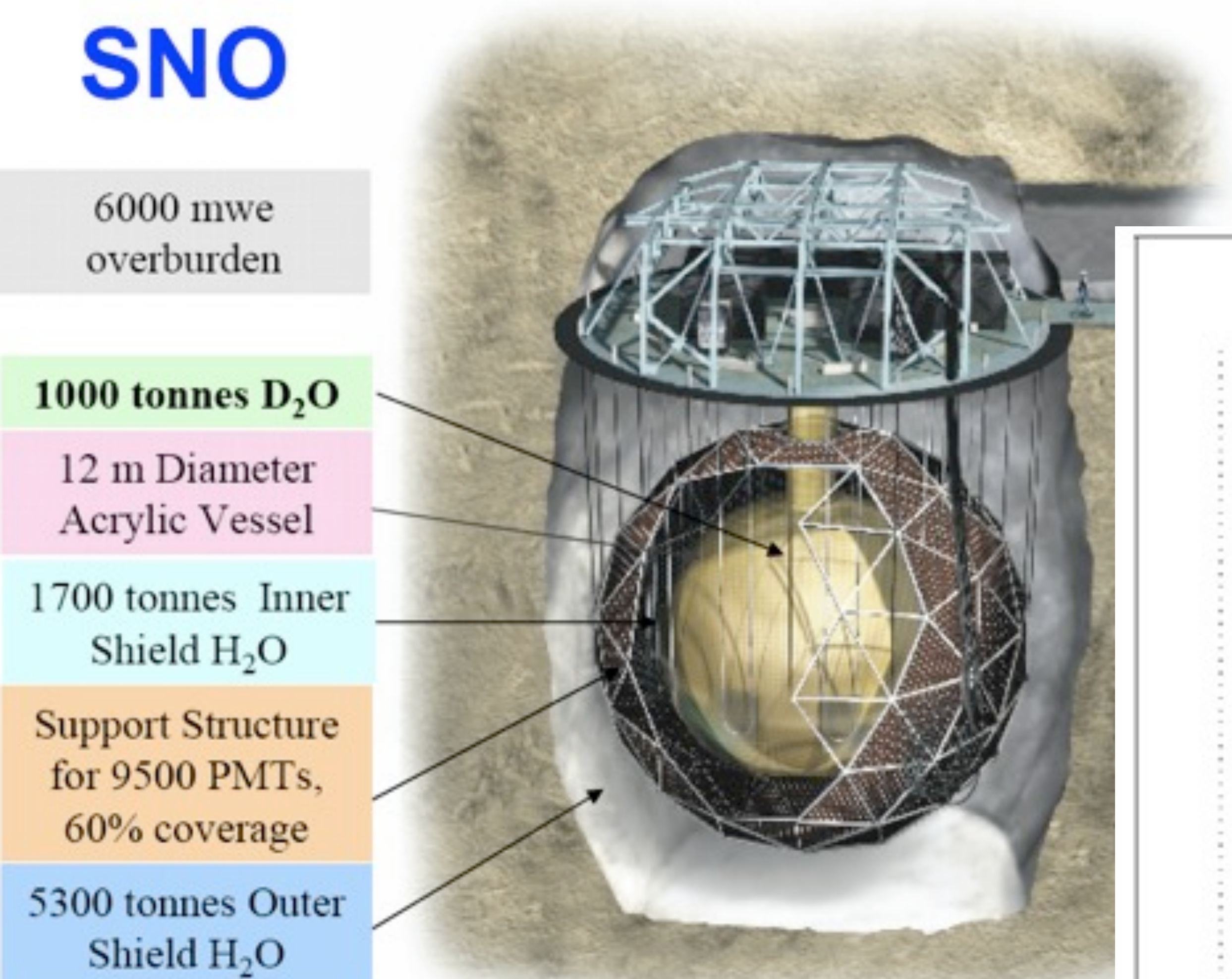
Neutrino detectors

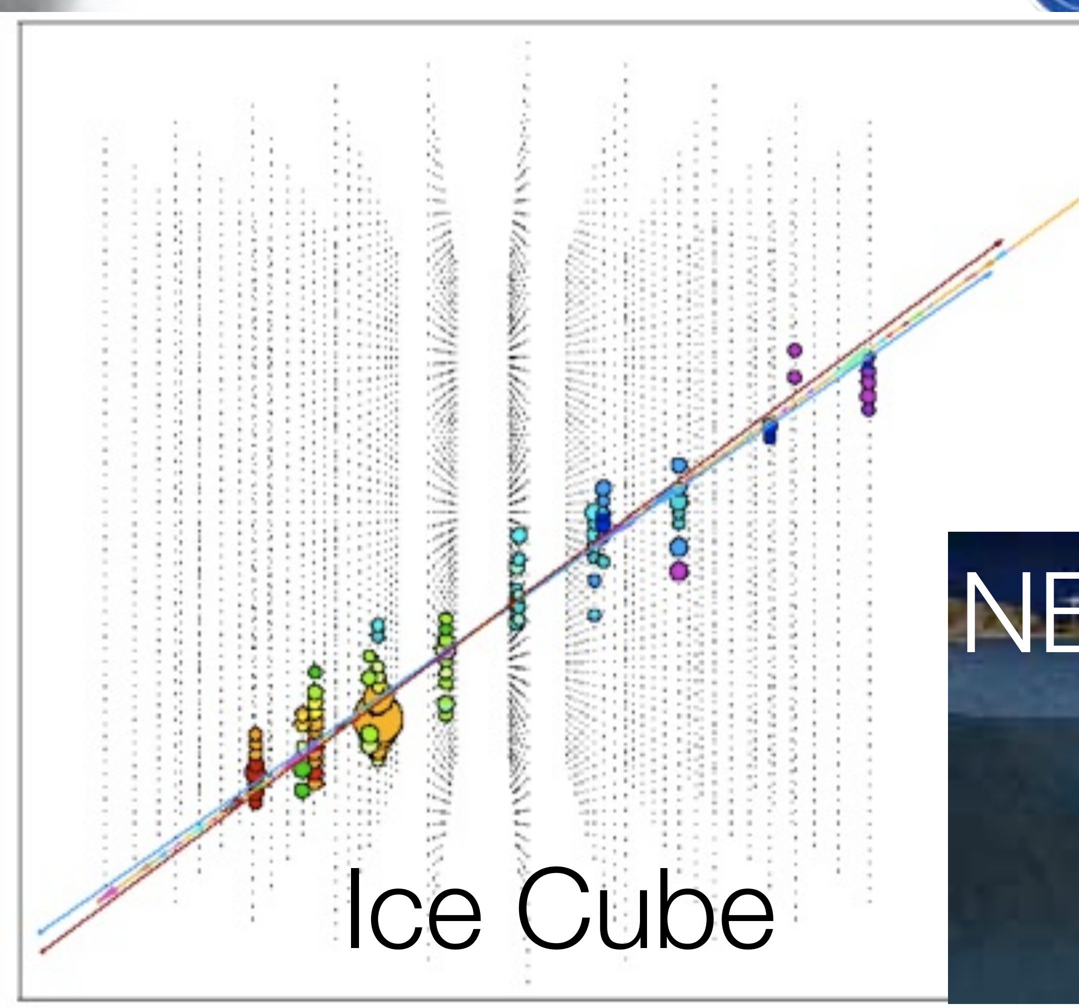
Topics for the remaining two lectures

- Today
  - Cherenkov detectors
  - Tracking calorimeters
- Thursday
  - tau neutrino detection
  - Large liquid scintillator detectors
  - Time projection chambers

Cherenkov detectors

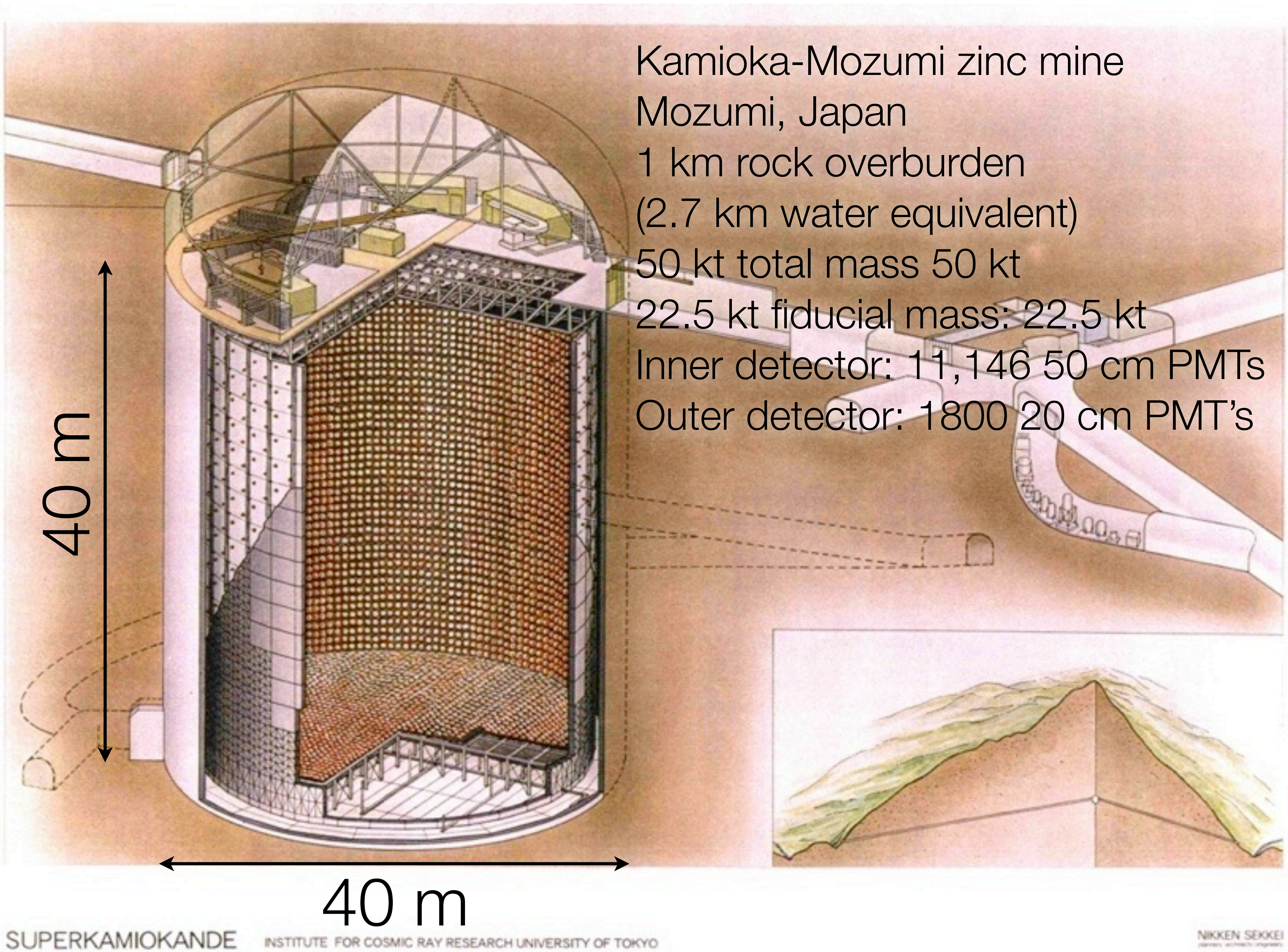






Super-Kamiokande

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

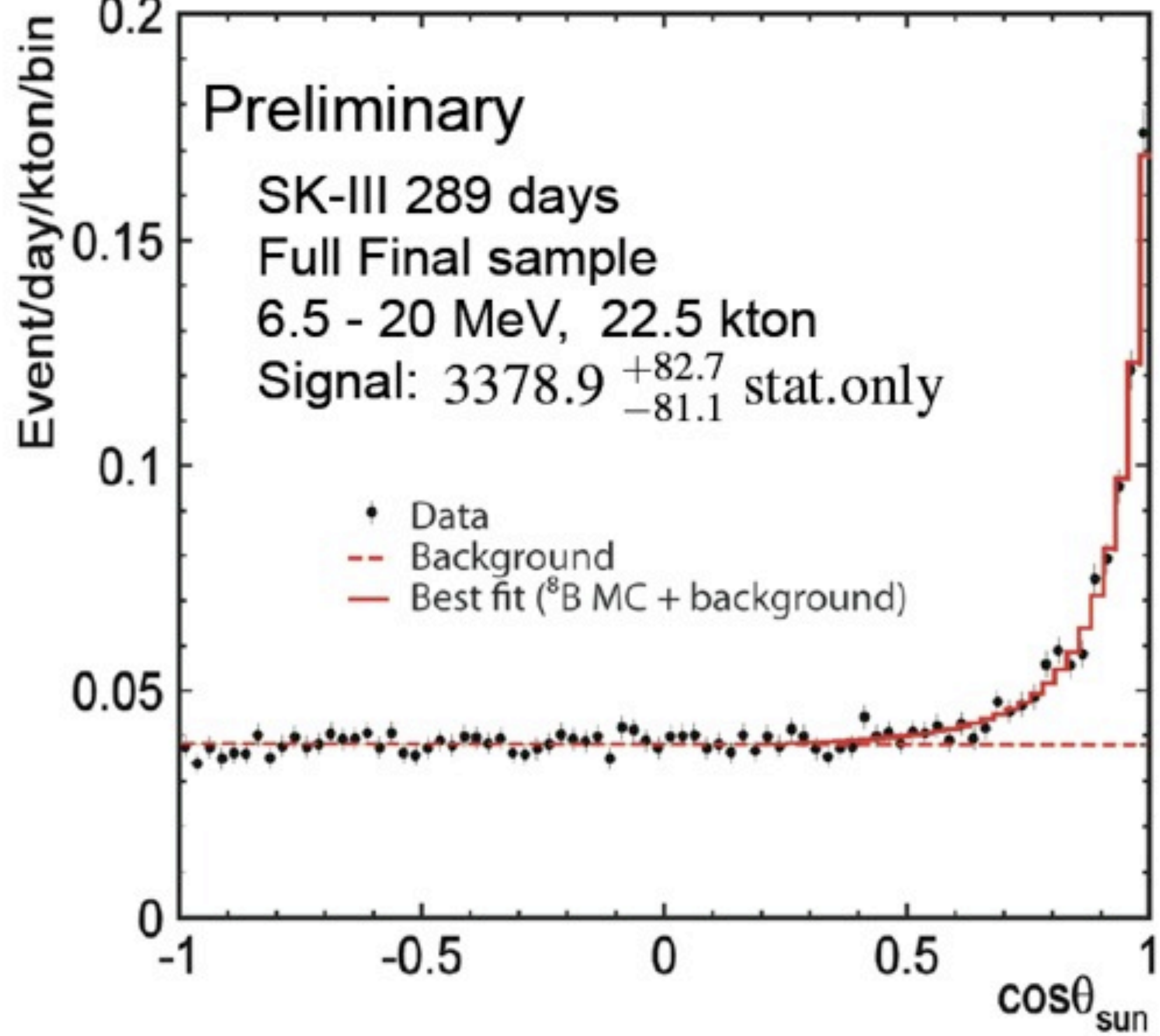


General performance

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

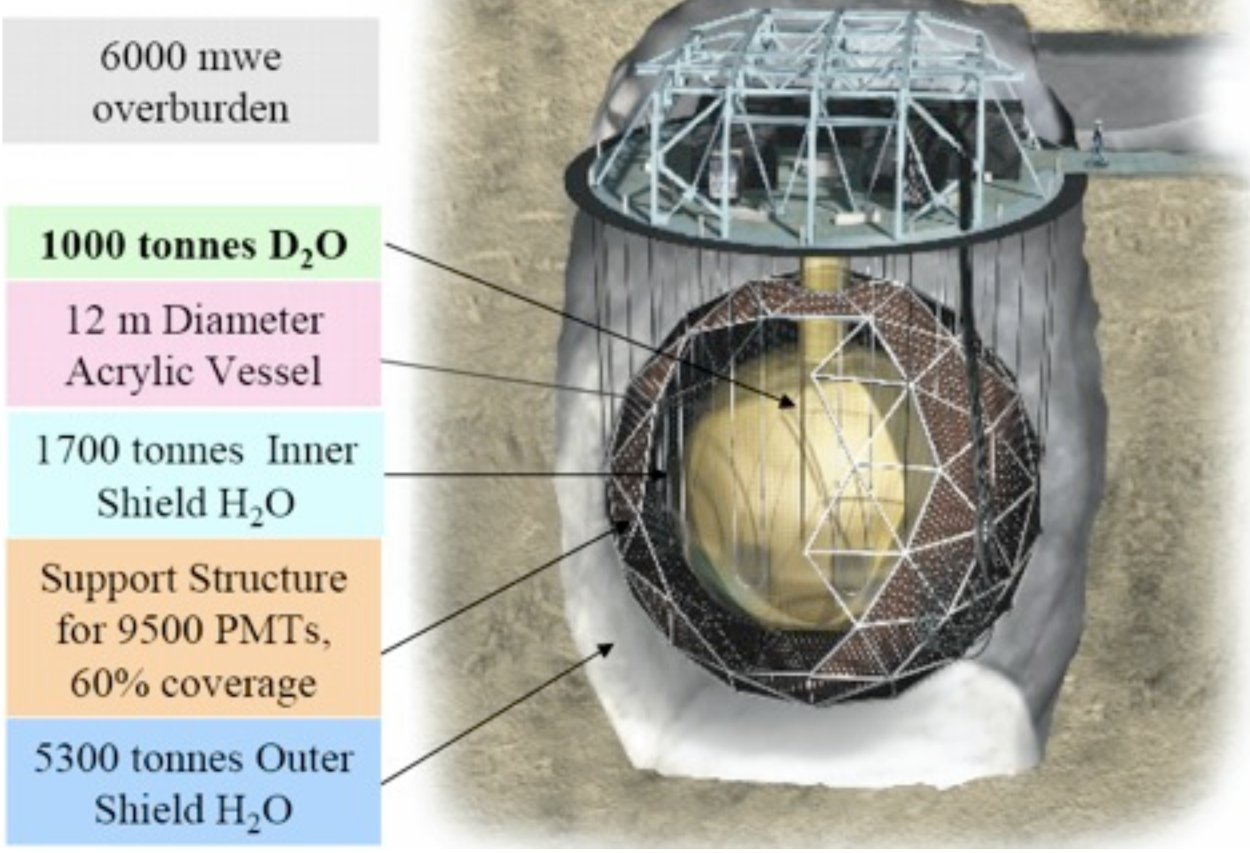
- Tracks produce rings on the walls. In high multiplicity events overlap of rings makes reconstruction difficult. Typically, analyses focus on quasi-elastic events which are very often single-track events.

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

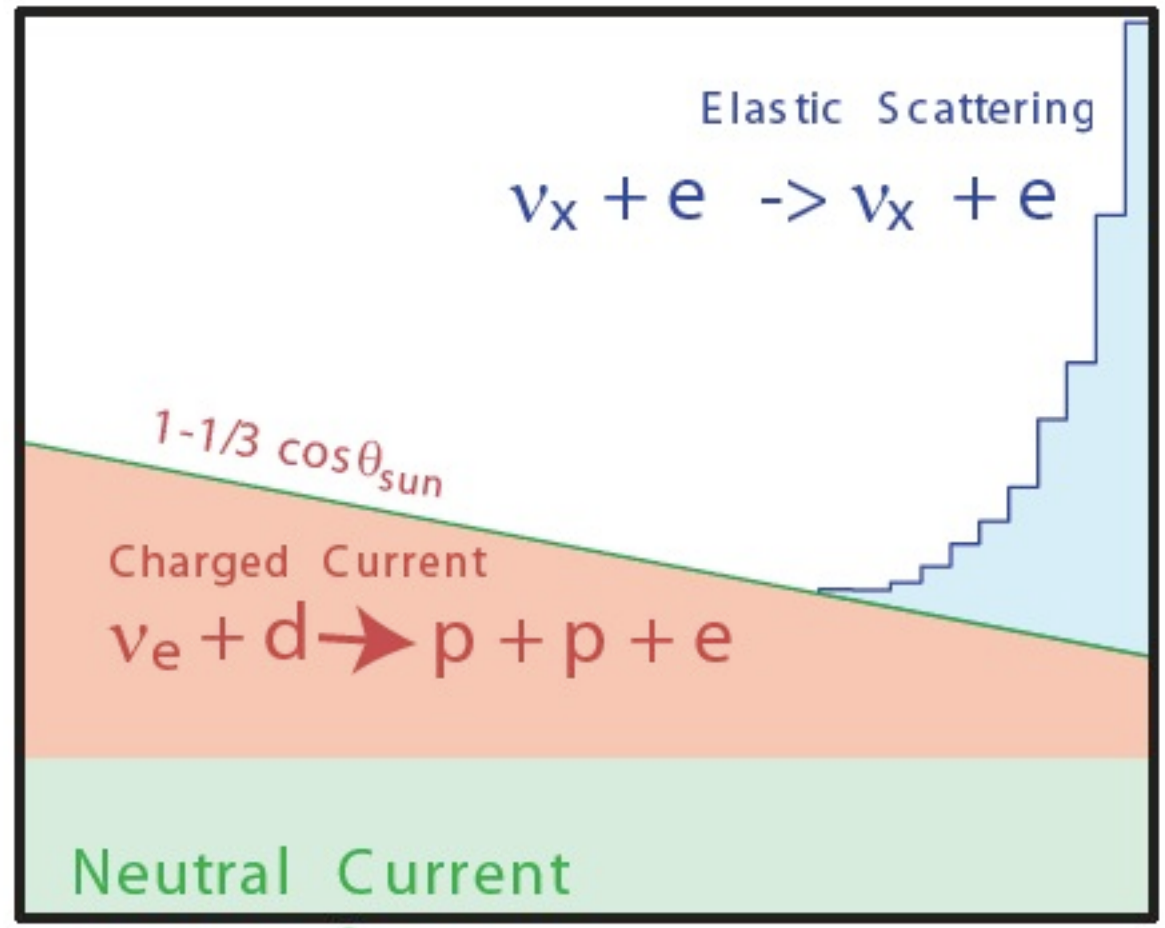


- Events with pions (and other tracks) that are below Cherenkov threshold lead to backgrounds for the quasi-elastic selection

SNO



Angle between ν and sun



- SNO detector used 1 kt D_2O instead of ordinary water. Provided additional detection channels at low energy:

$$\nu_x + e^- \to \nu_x + e^- \quad \text{ES = CC + 1/6 NC}$$
$$\nu_e + d \to p + p + e^- \quad \text{CC}$$
$$\nu_x + d \to p + n + \nu_x \quad \text{NC}$$

- Neutron tagging by:

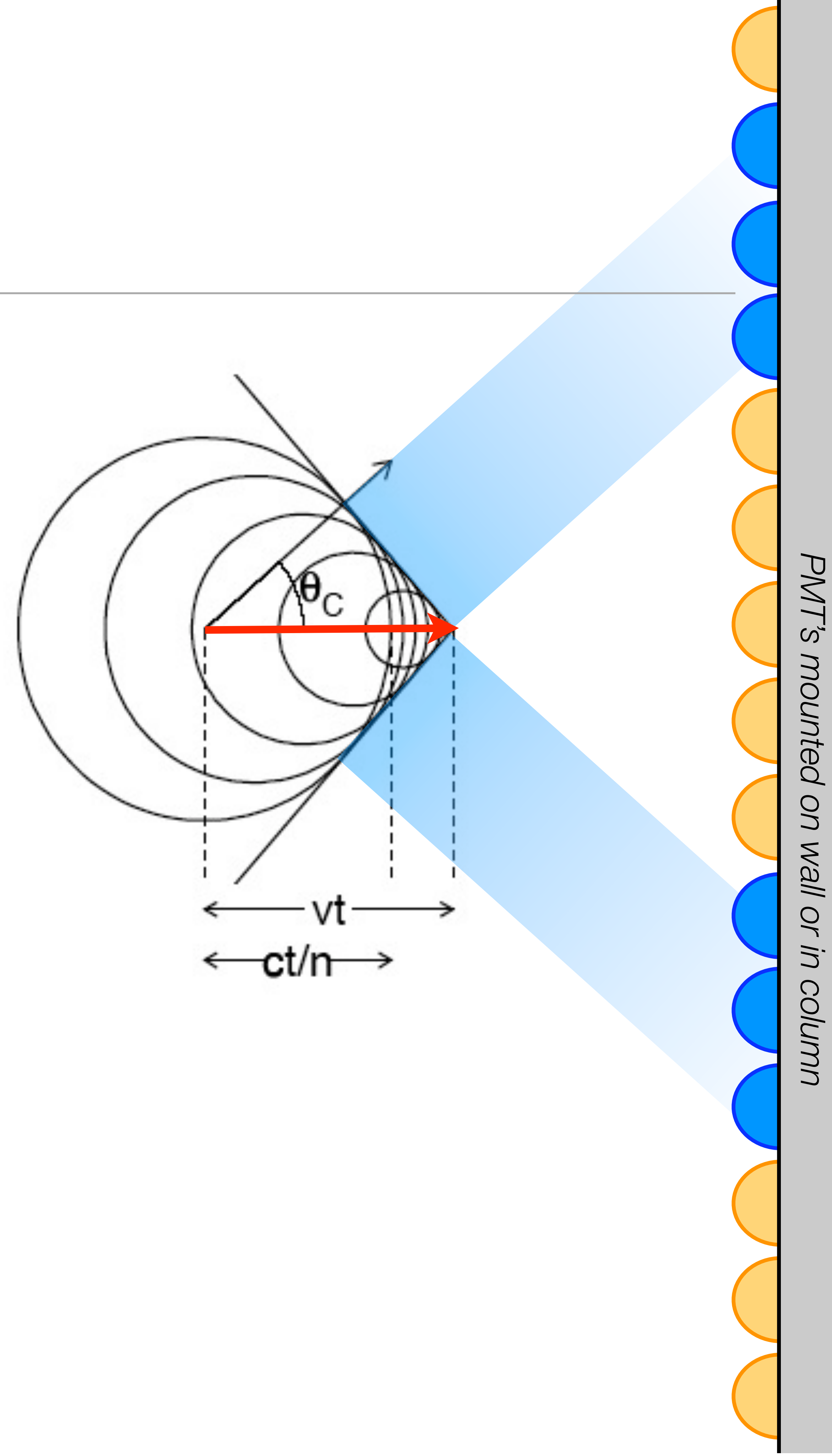
$$n + d \to t + \gamma + 6.25 \text{ MeV}$$
$$n + {}^{35}Cl \to {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$
$$n + {}^{3}He \to p + t + 0.76 \text{ MeV}$$

Cherenkov effect

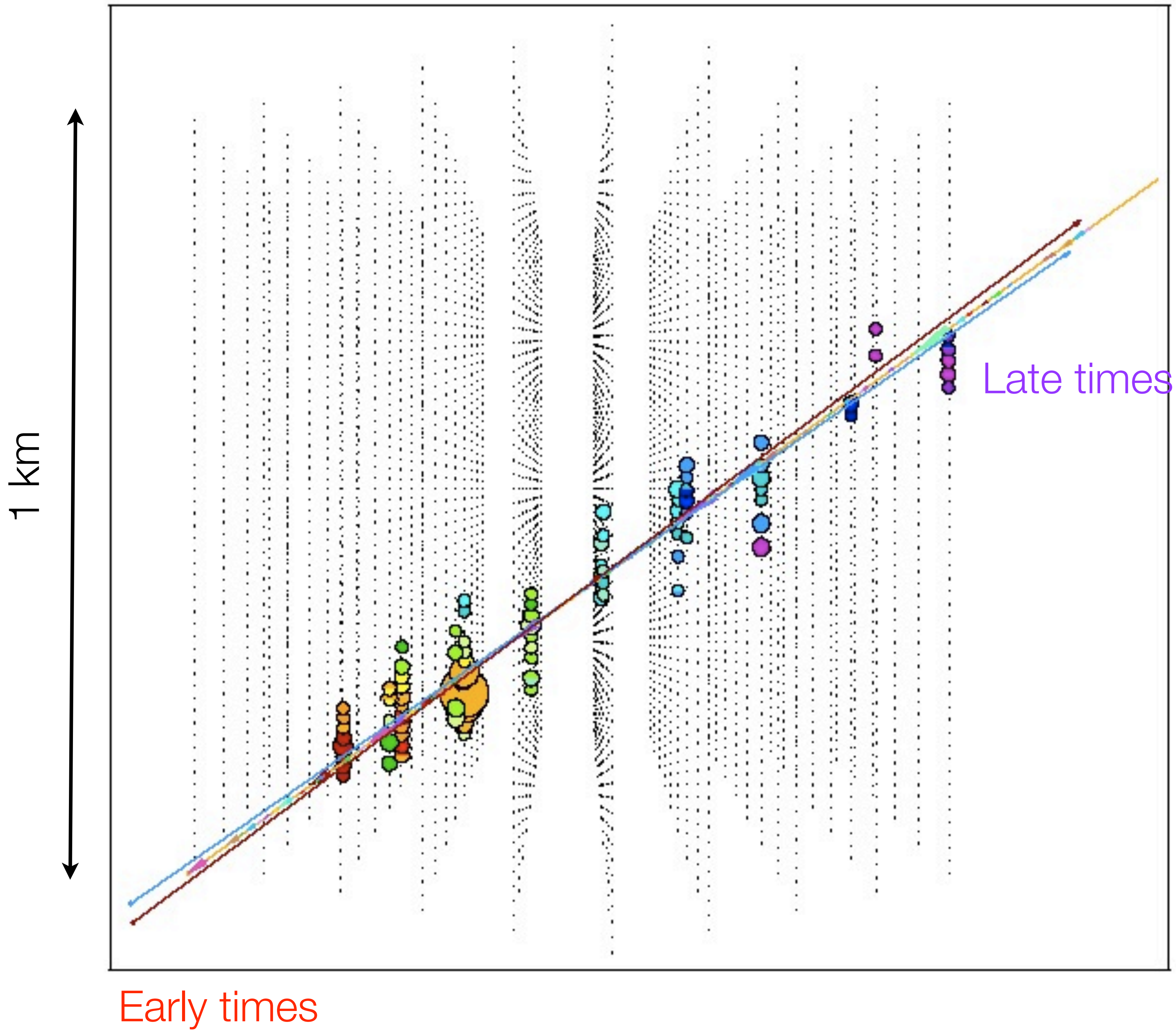
- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction *n*, a "shock wave" of radiation develops at a critical angle: $$\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$
- PMTs record time and charge which provide unique solution for track position and direction. For Nhit PMTs measuring light arrival time t, minimize:

$$\chi^2 = \sum_{i=1}^{N_{\rm hit}} \frac{(t_i - TOF_i)^2}{\sigma_t^2}$$

where TOF is the time of flight for photons to go from the track to the PMT



10 TeV neutrino induced muon neutrino in Ice Cube



Times differ by roughly 2.5 usec. For PMT with ~10 ns time resolution this gives an up vs. down discrimination of > 250 sigma !

Cherenkov effect

- Threshold means that slow particles produce no light. As particles come to a stop their rings collapse. Useful for particle ID near threshold.

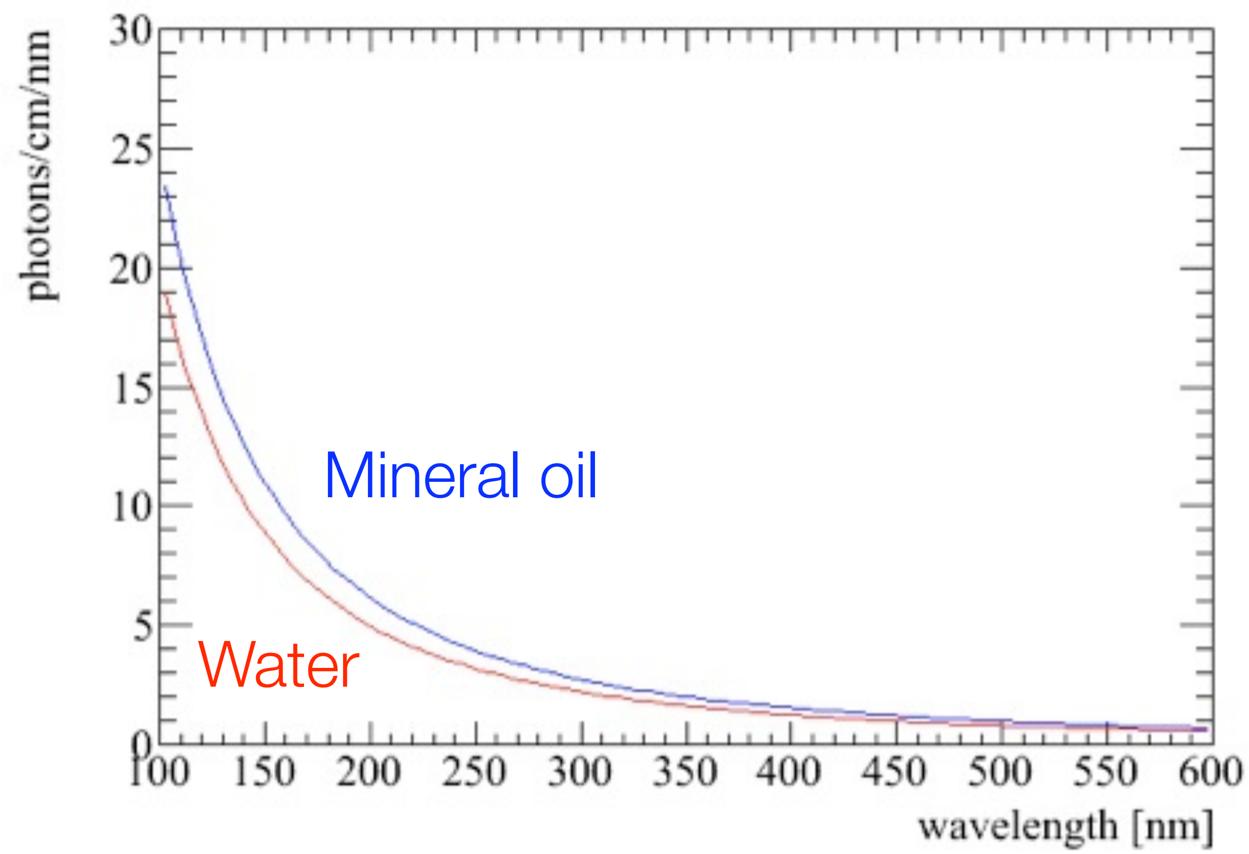
$$p_{\text{thresh}} = m\sqrt{\frac{1}{n^2-1}}$$

		p_{thresh} [MeV/c]					θ_C	
		e	μ	π	K	p	$\beta = 1$	$\beta = 0.9$
Water	n = 1.33	0.58	120	159	563	1070	42	33
Mineral Oil	n = 1.46	0.47	98	130	458	817	47	41

- Number of photons produced per unit path length:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right) = 370 \sin^2\theta_C(E)/\text{eV/cm}$$

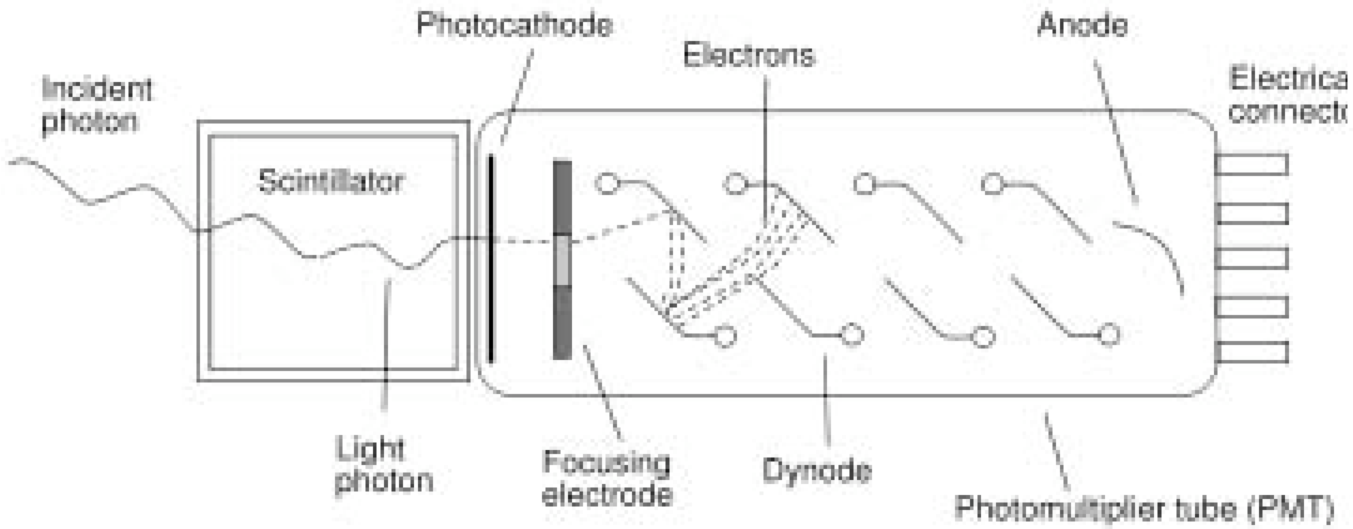
- In both oil and water the useful part of this spectrum is between 300 and 600 nm bracketed by Rayleigh scattering on the low end and absorption on the high end



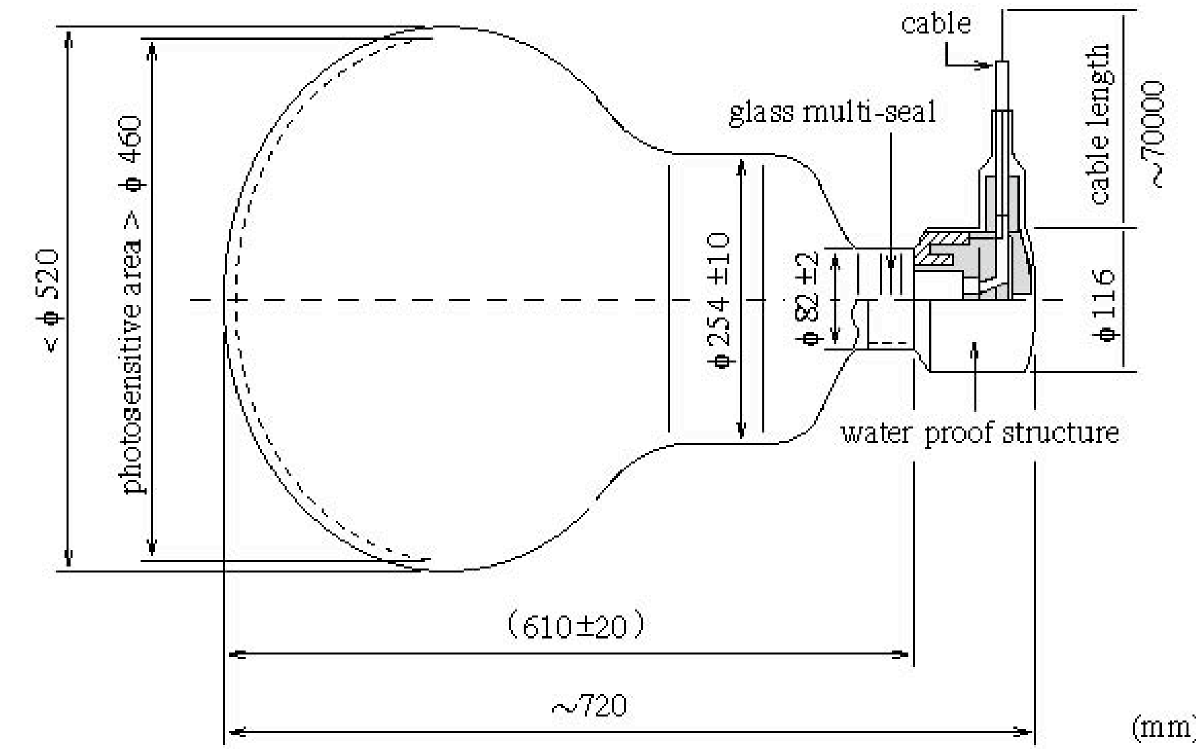
Photomultiplier tubes

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.

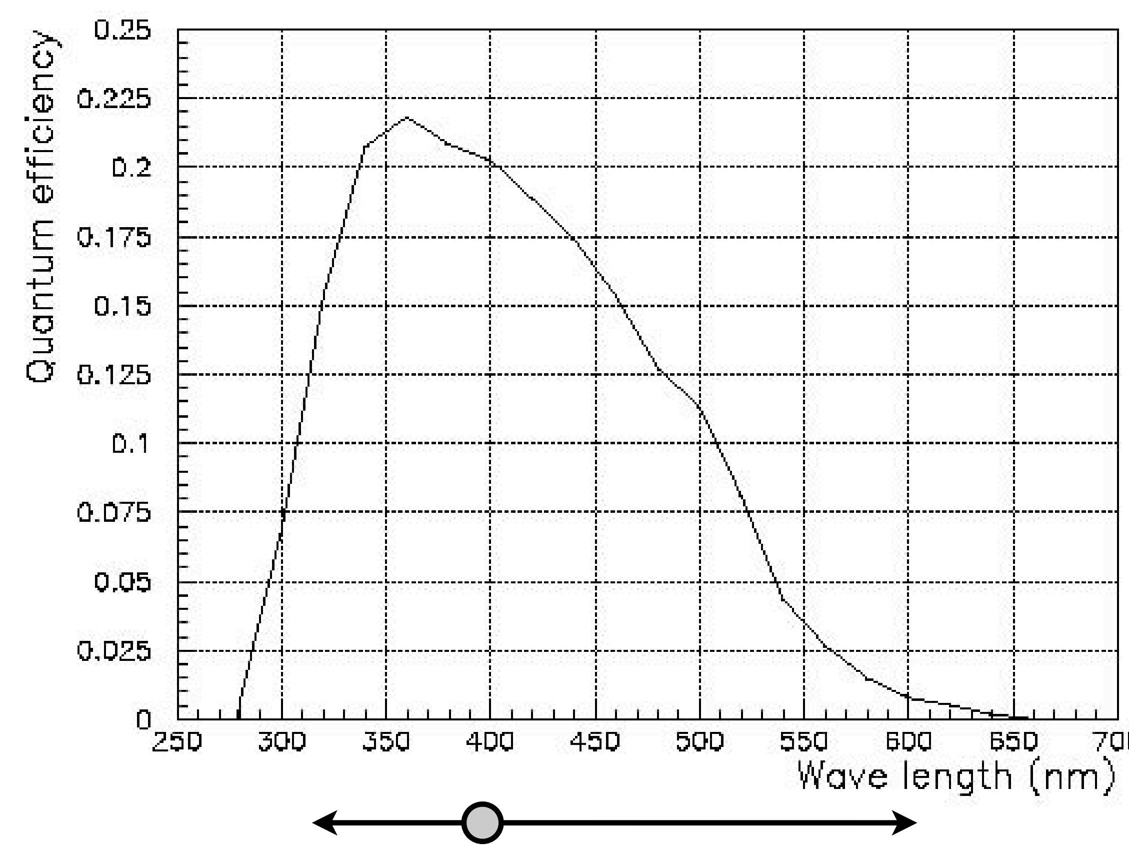
Output signal is seen as a current delivered to the *anode*. Typical *gains* are 10^6 yielding pC-scale currents



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

Quiz

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume 40% of the detector walls are covered by PMT's and that the PMT's have an average of 25% efficiency. Estimate the energy resolution at this energy.

Quiz

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume 40% of the detector walls are covered by PMT's and that the PMT's have an average of 25% efficiency. Estimate the energy resolution at this energy.

A: A 10 MeV electron will go about 5 cm in the tank making about N = 370*sin(42^o)^2 = 160 photons. Of those (0.4*0.25) = 0.1 will be detected. So I have ~16 detected photons each with a timing resolution of 2 ns ~= (60 cm * 1.33) = 80 cm since the speed of light is n * 30 cm/ns. This gives a final resolution of about: 80 cm/sqrt(16) = *20 cm.* Energy resolution dominated by Poisson fluctuations on the number of photons collected. In this case ~sqrt(16)/16 = *25%*.

Quiz

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume 40% of the detector walls are covered by PMT's and that the PMT's have an average of 25% efficiency. Estimate the energy resolution at this energy.

A: A 10 MeV electron will go about 5 cm in the tank making about N = $370 * \sin(42^{o})^{2}$ = 160 photons. Of those (0.4*0.25) = 0.1 will be detected. So I have ~16 detected photons each with a timing resolution of 2 ns ~= (60 cm * 1.33) = 80 cm since the speed of light is n * 30 cm/ns. This gives a final resolution of about: 80 cm/sqrt(16) = *20 cm.* Energy resolution dominated by Poisson fluctuations on the number of photons collected. In this case ~sqrt(16)/16 = *25%*.

Q: Compare the detection efficiencies for the Kamiokande (20% photocathode coverage) and IMB-1 (1% photocathode coverage) for a 15 MeV super-nova neutrino

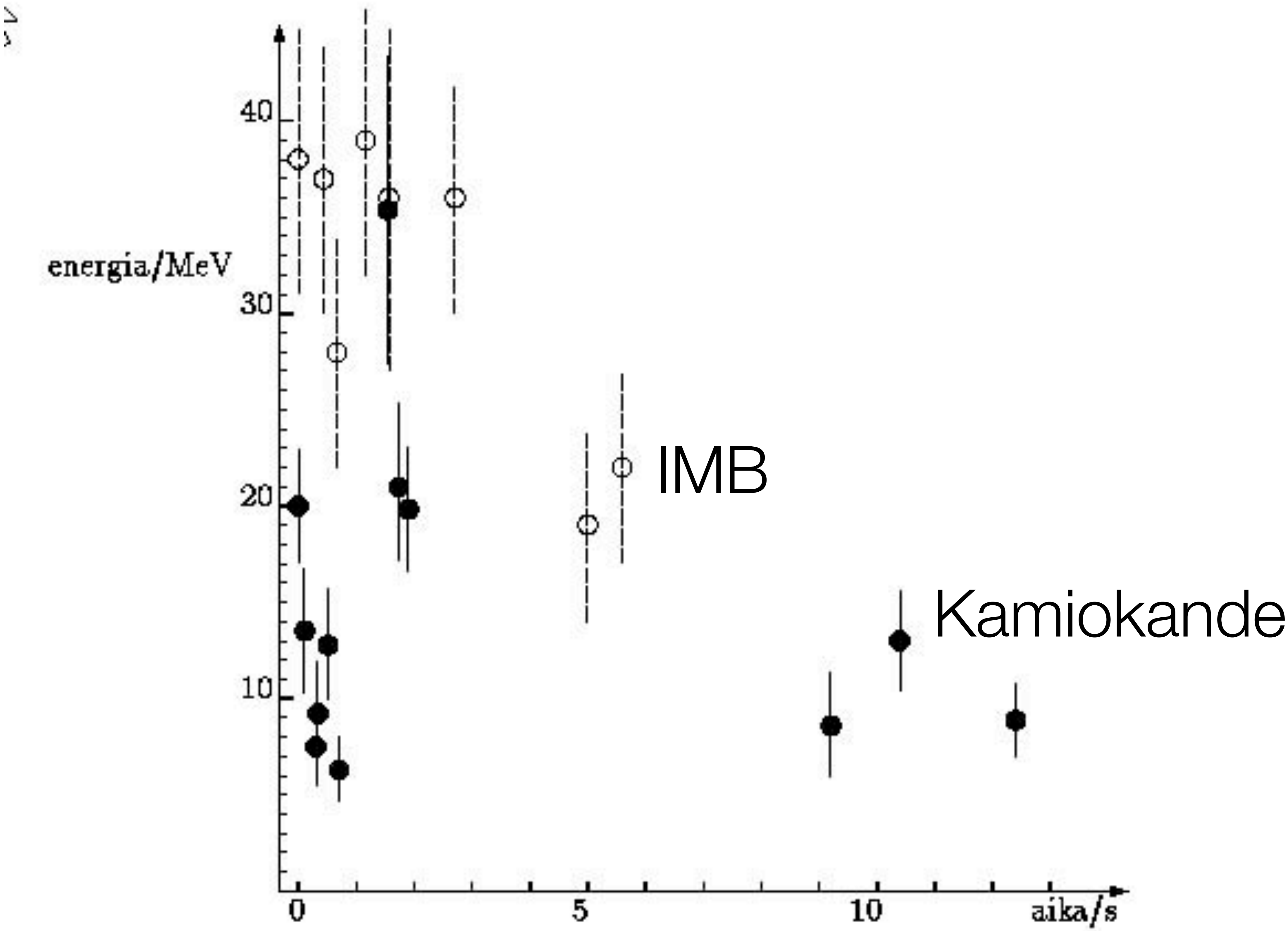
Quiz

Q: Estimate the vertex resolution for a water Cherenkov detector for a 10 MeV electron produced by the elastic scatter of a solar neutrino. Assume 40% of the detector walls are covered by PMT's and that the PMT's have an average of 25% efficiency. Estimate the energy resolution at this energy.

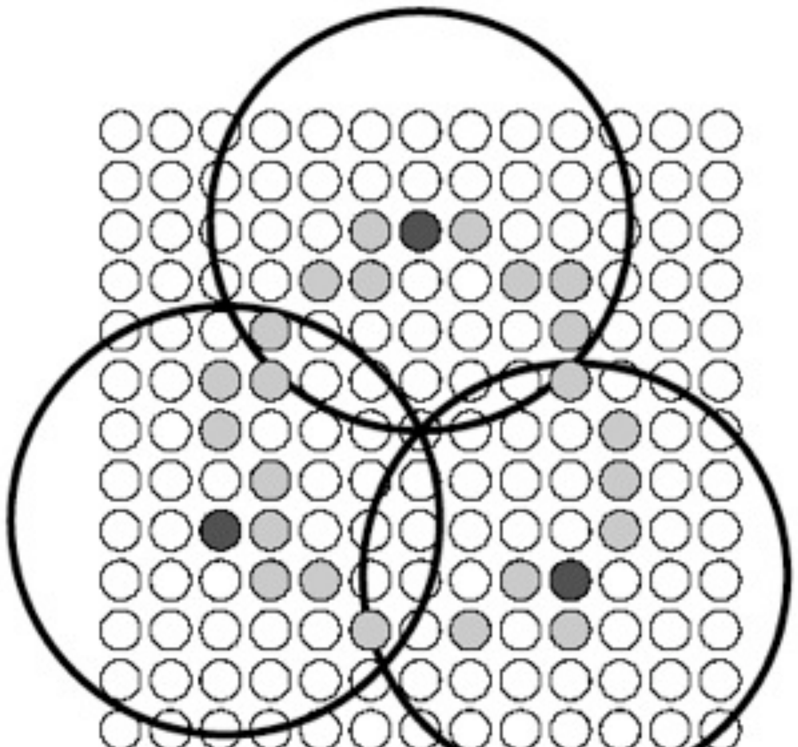
A: A 10 MeV electron will go about 5 cm in the tank making about N = $370 * \sin(42^o)^2$ = 160 photons. Of those (0.4*0.25) = 0.1 will be detected. So I have ~16 detected photons each with a timing resolution of 2 ns ~= (60 cm * 1.33) = 80 cm since the speed of light is n * 30 cm/ns. This gives a final resolution of about: 80 cm/sqrt(16) = *20 cm.* Energy resolution dominated by Poisson fluctuations on the number of photons collected. In this case ~sqrt(16)/16 = *25%*.

Q: Compare the detection efficiencies for the Kamiokande (20% photocathode coverage) and IMB-1 (1% photocathode coverage) for a 15 MeV super-nova neutrino

A: 15 MeV corresponds to about 240 photons which is about 0.6 detected photons on average in IMB and 12 in Kamiokande. Efficiency for detection is roughly 1-exp(-0.6) = 45% for IMB and 1-exp(-12) = 99.99% for Kamiokande.


energia/MeV
40
30
20
10
0
5
10
aika/s
IMB
Kamiokande

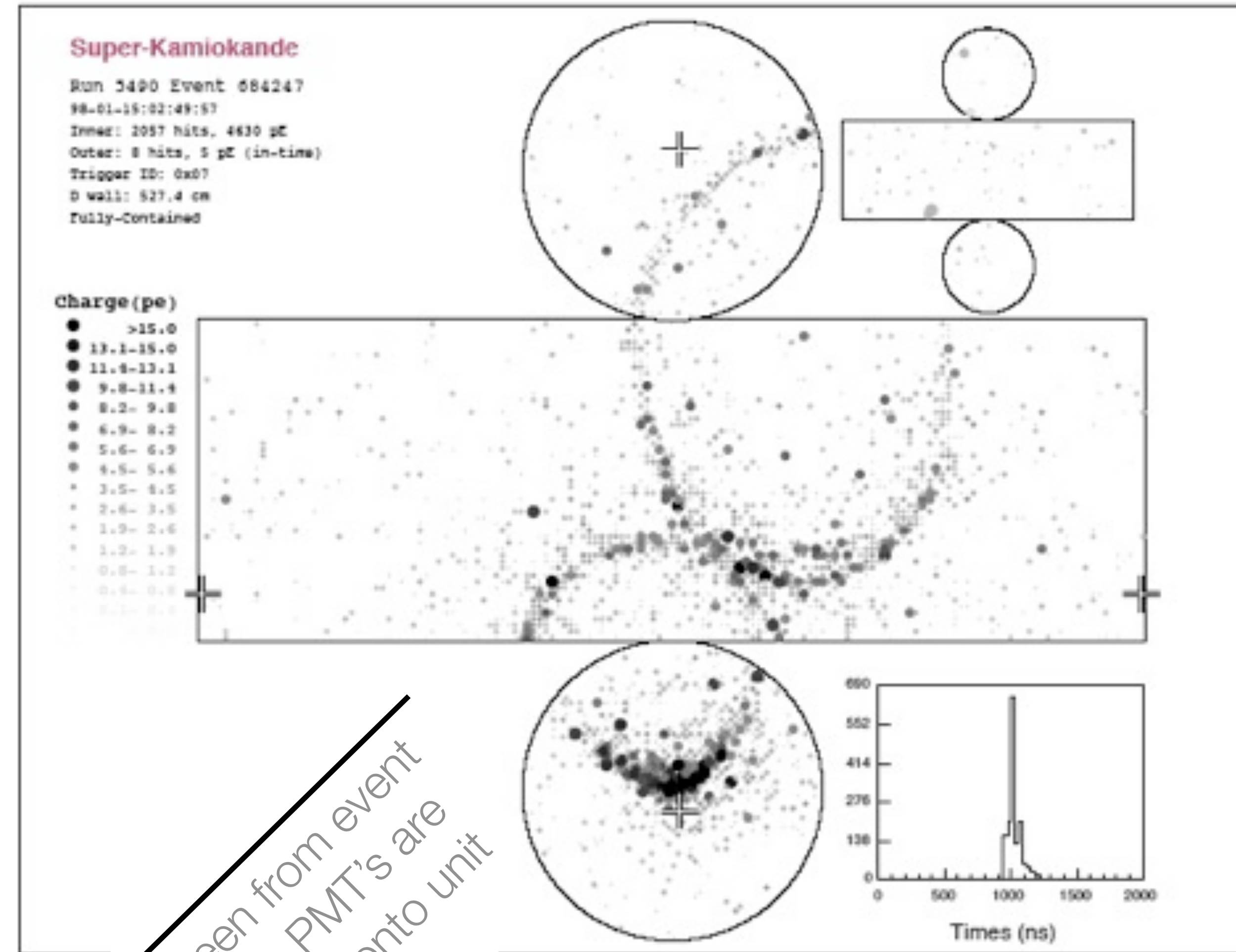
Water Cherenkov: Ring Counting



PMT array

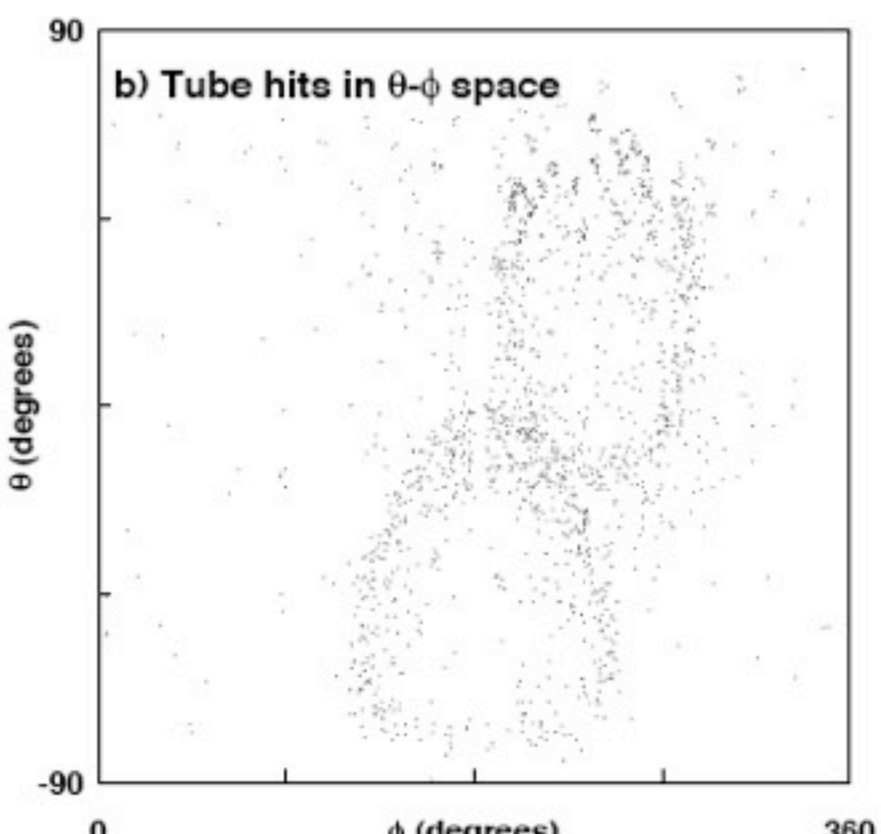
Circles overlap in center of ring corresponding to direction of particle

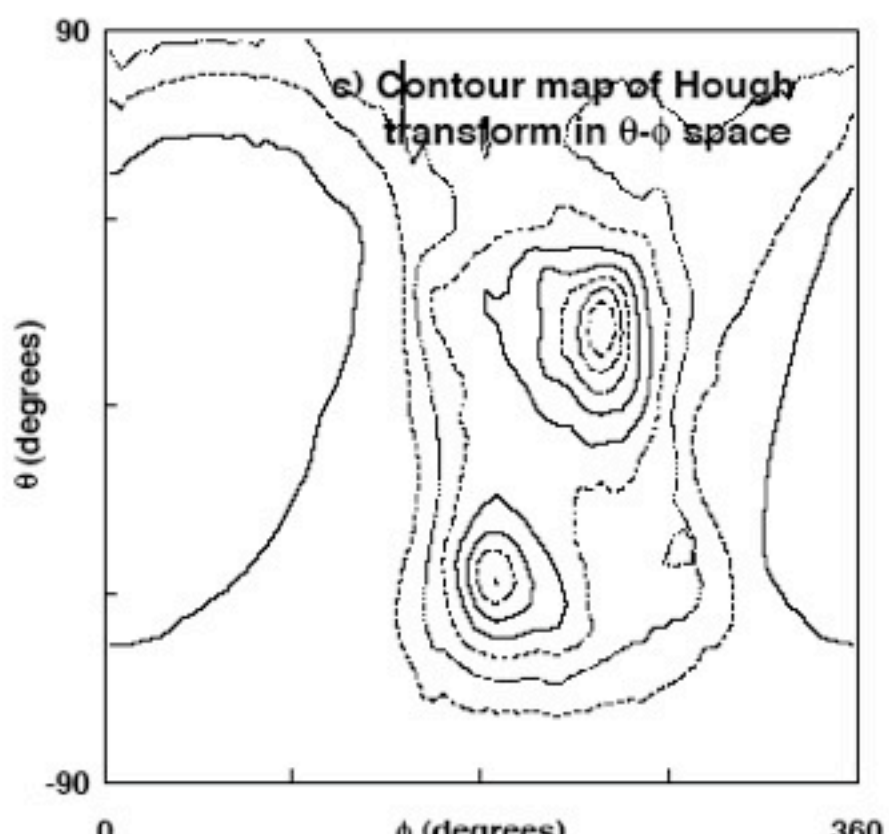
If you know the pattern you are looking for (line, circle, oval, etc.) the Hough transform is a method for converting a pattern recognition problem to a peak finding problem



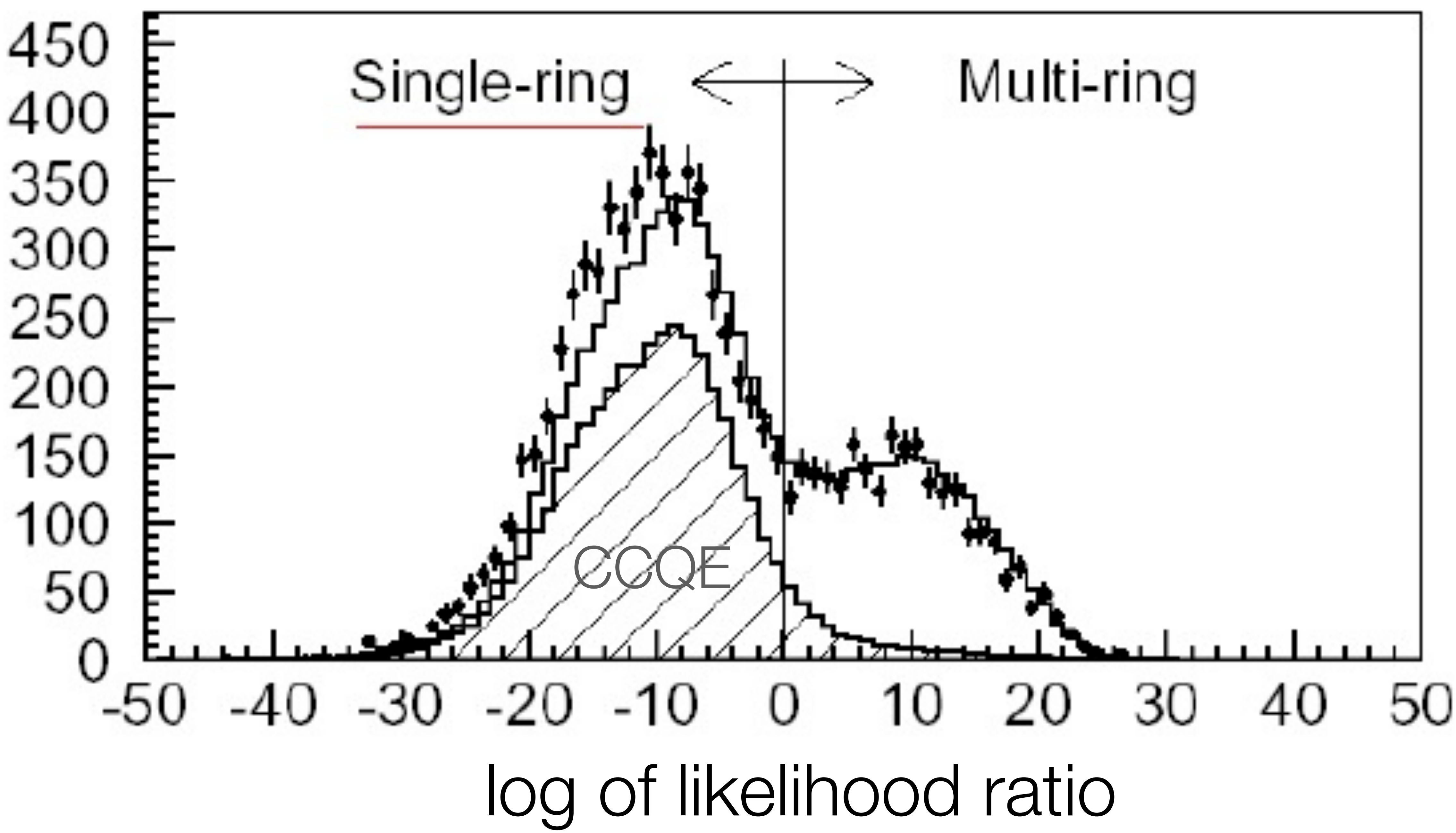
Figures from M. Earl's PhD Thesis

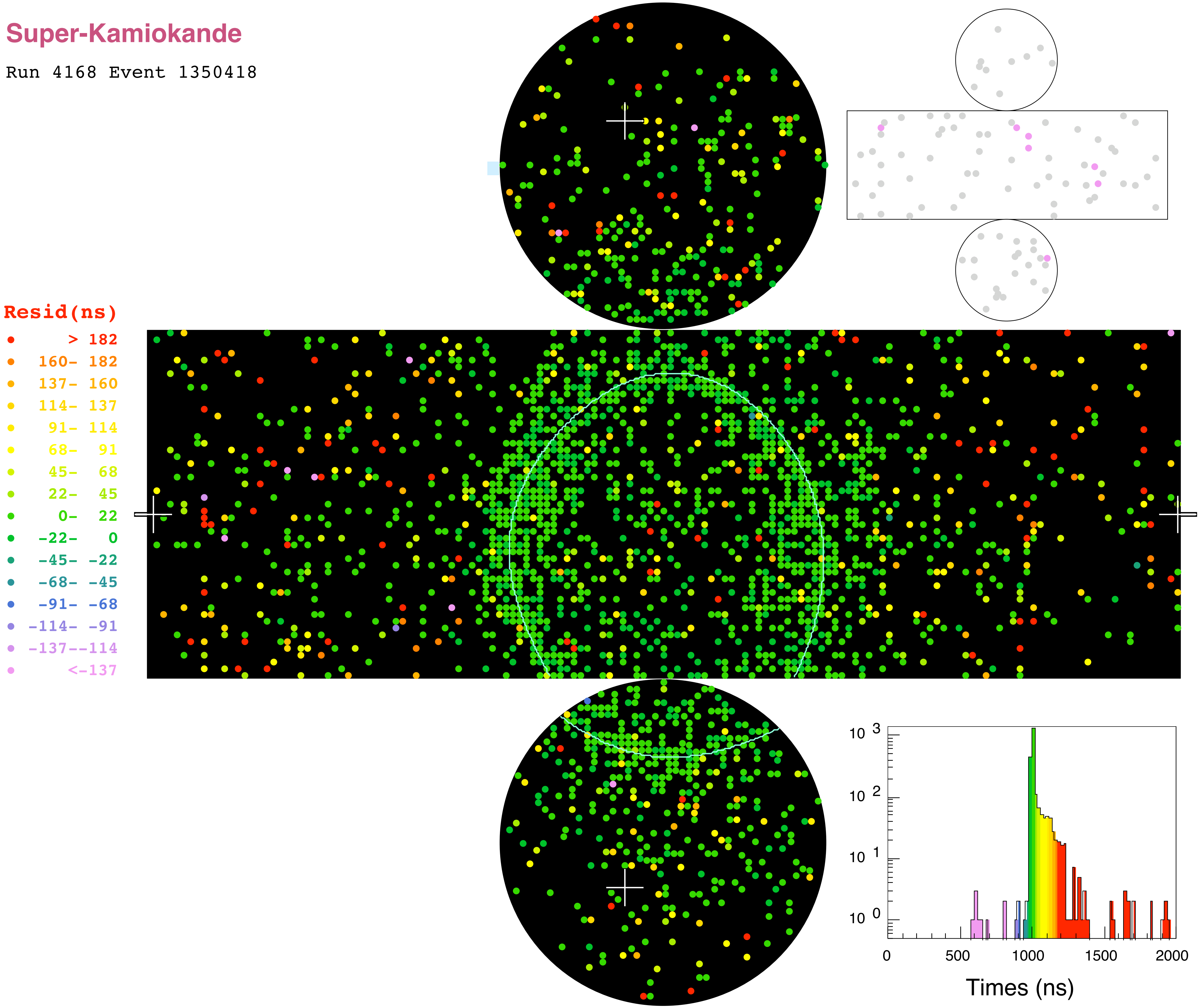
As seen from event vertex, PMT's are mapped onto unit sphere





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
Times (ns)

Quasi-elastic reconstruction $\nu_\mu + n \rightarrow \mu^- + p$

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

From 2 body kinematics

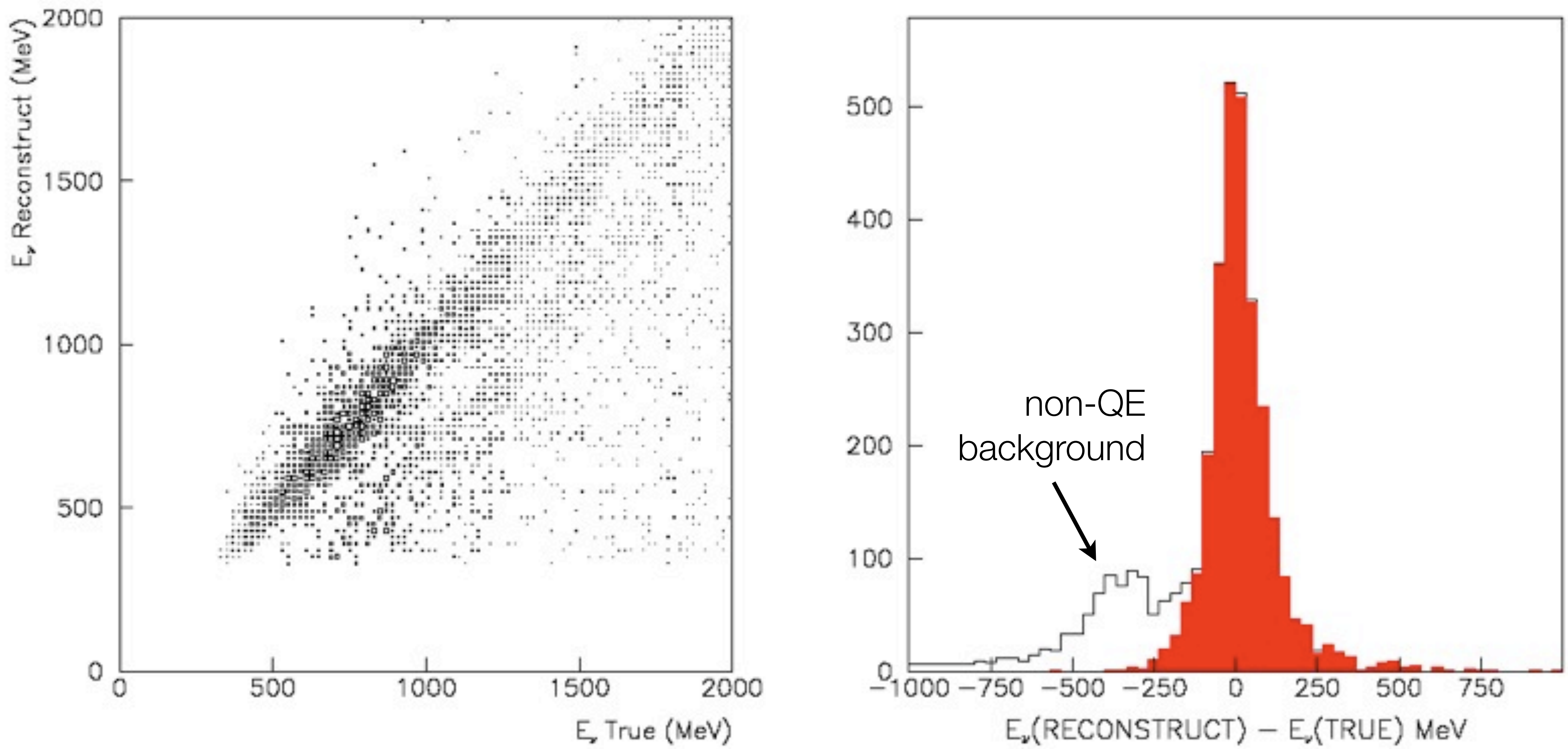
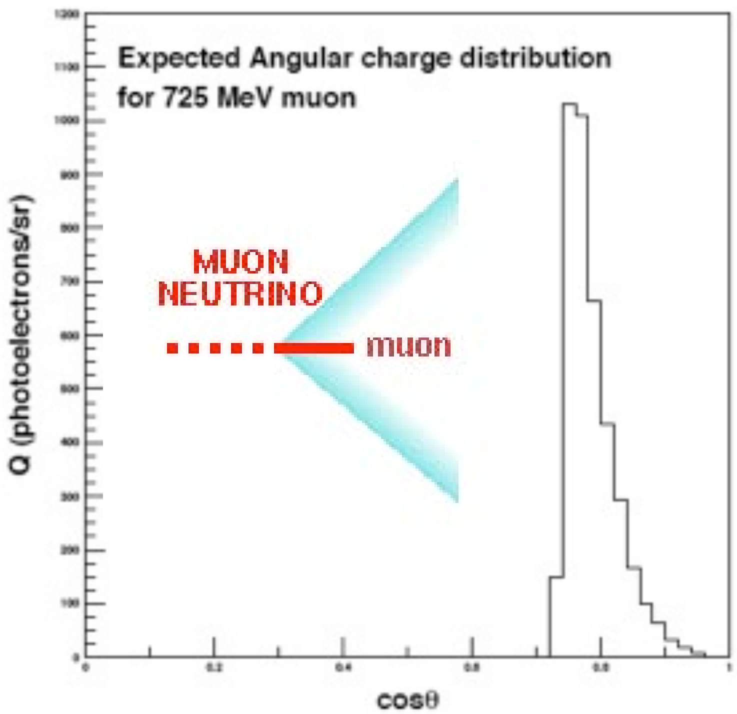


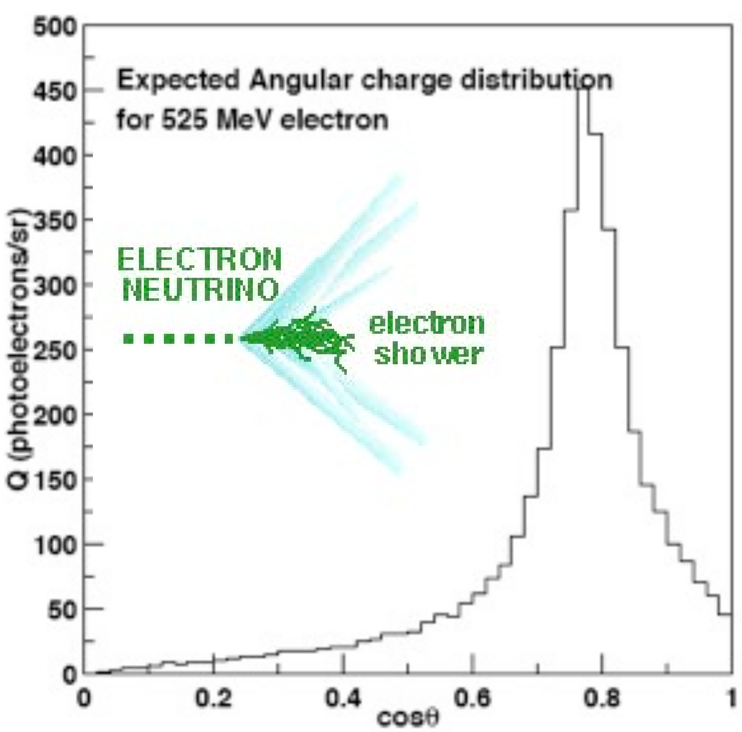
Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for ν_μ events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of ν_μ events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.

Water Cherenkov: e/μ identification

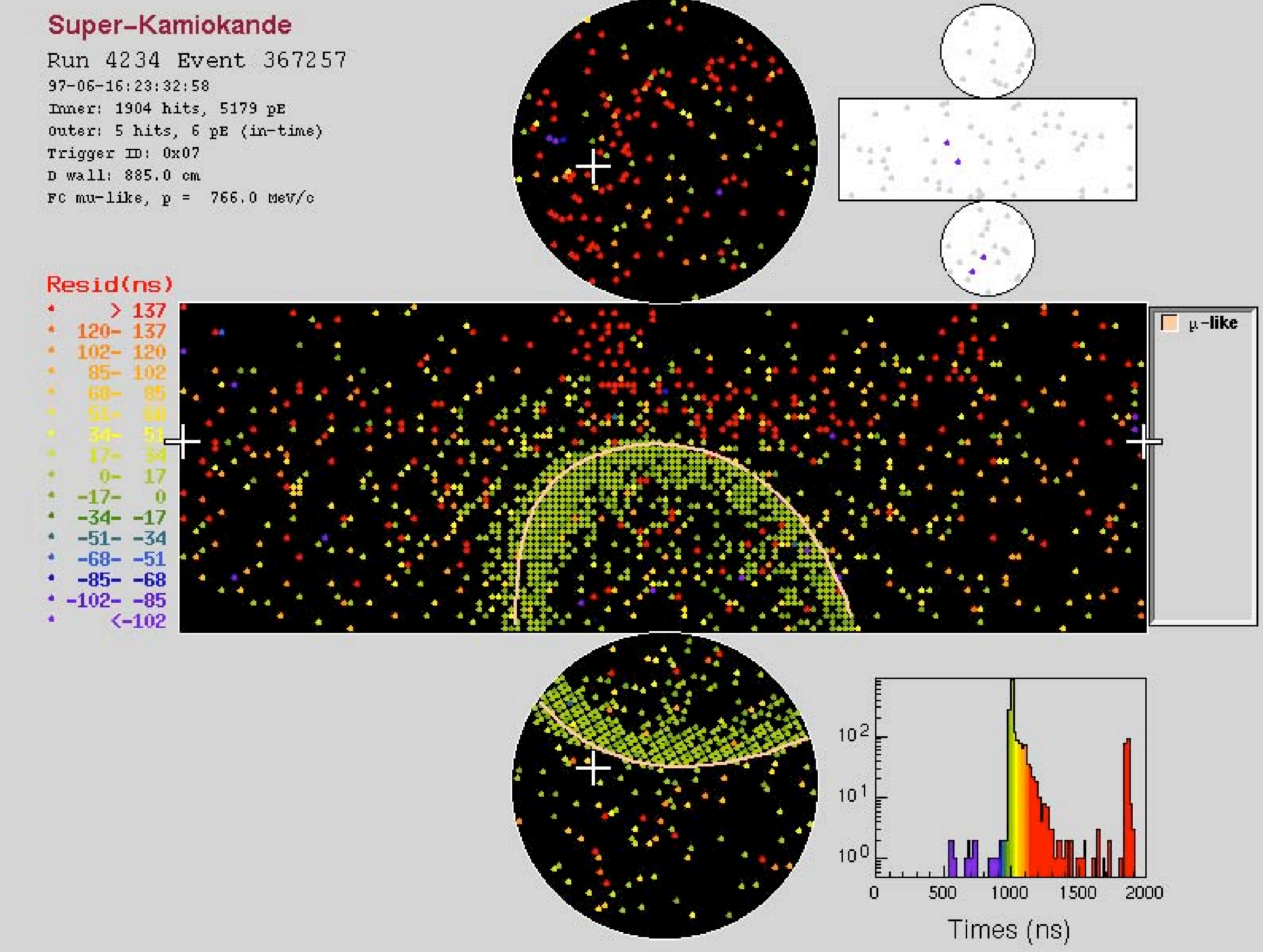
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42^{o}.

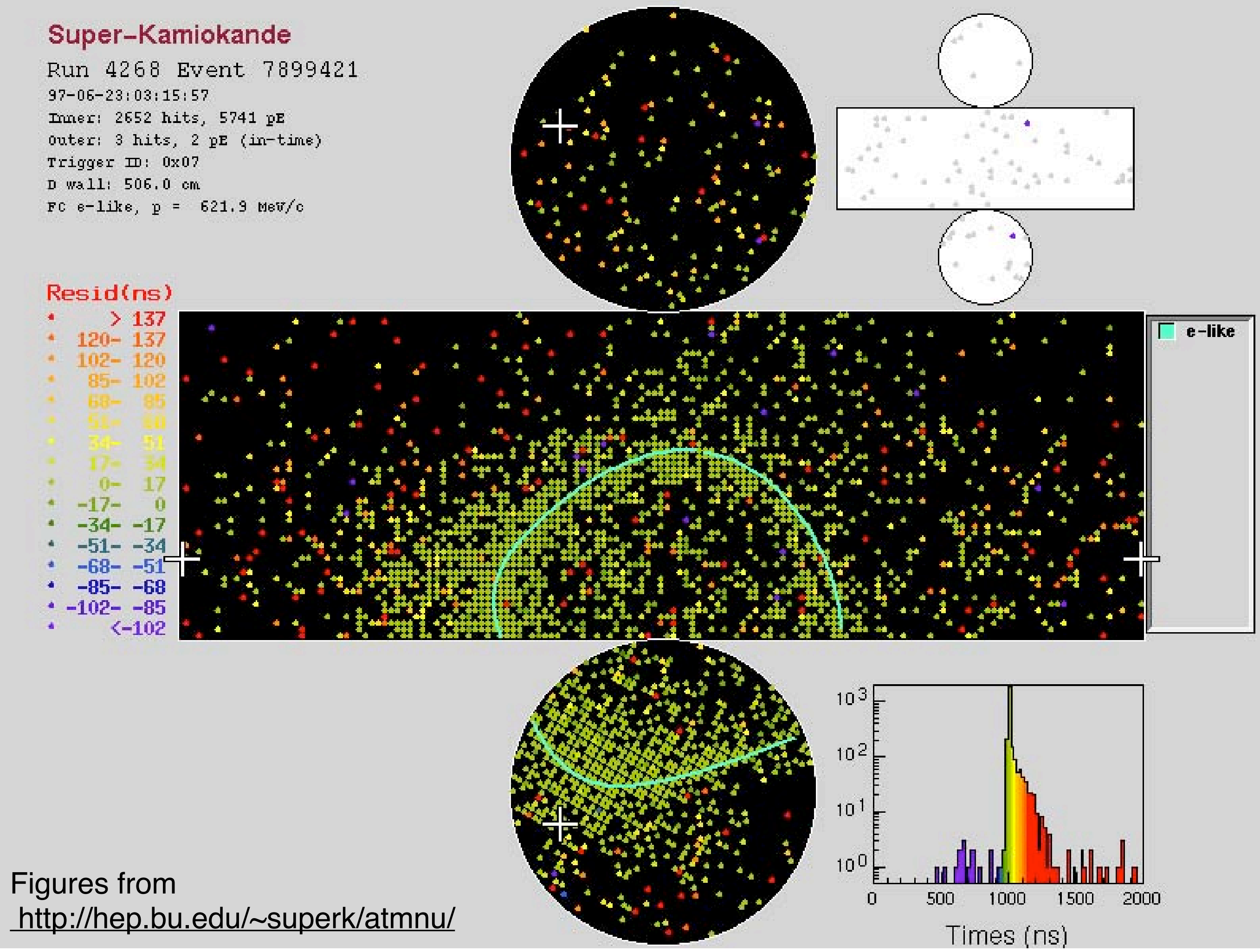


- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are “crisp”, electron showers are “fuzzy”. See plots and figures at the right.



Figures from M. Earl’s PhD Thesis

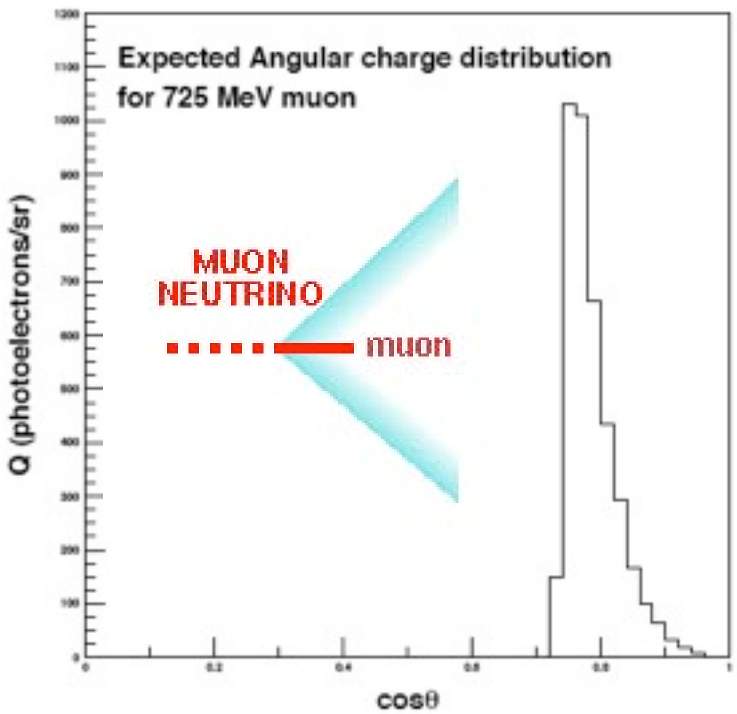




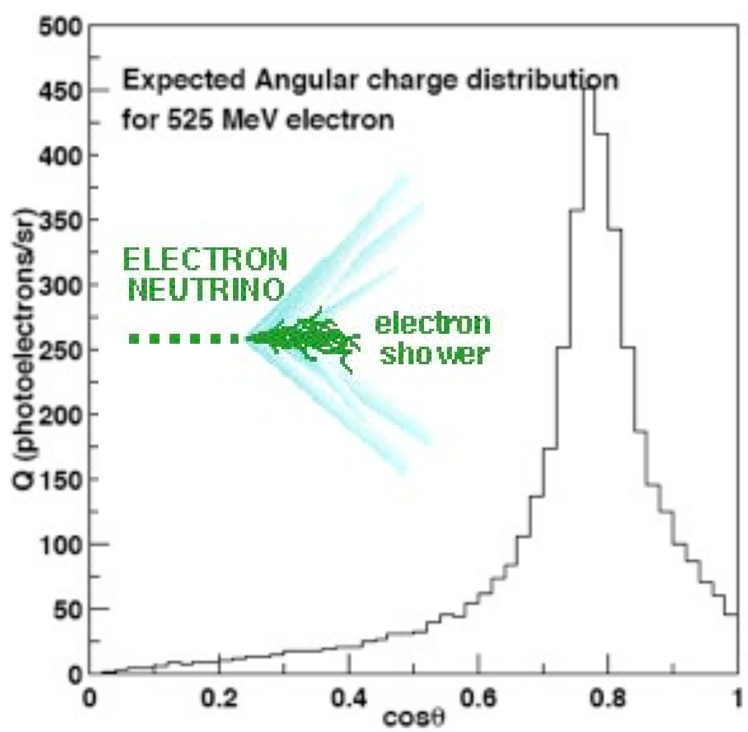
Figures from
http://hep.bu.edu/~superk/atmnu/

Water Cherenkov: e/μ identification

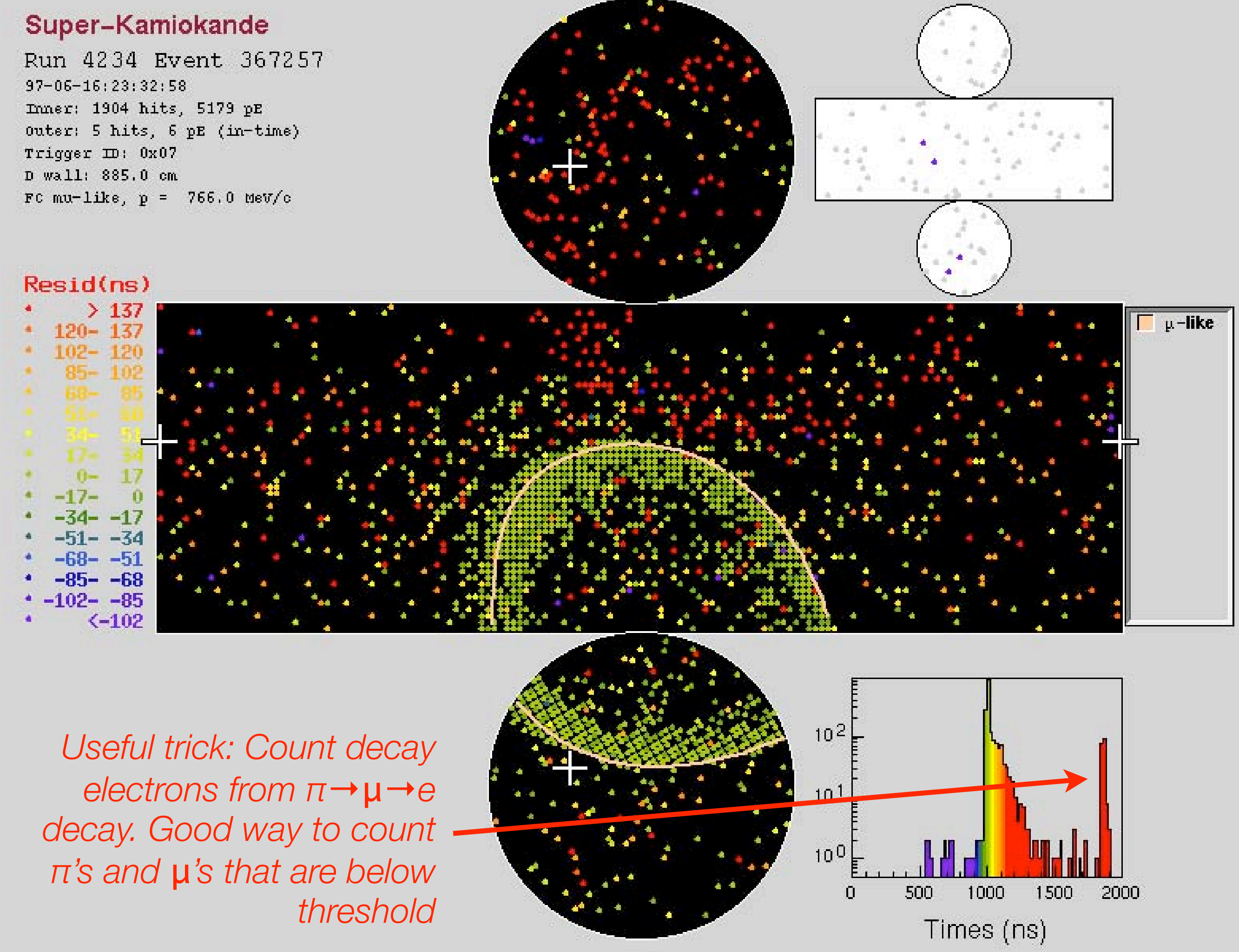
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are ~always at 42°.



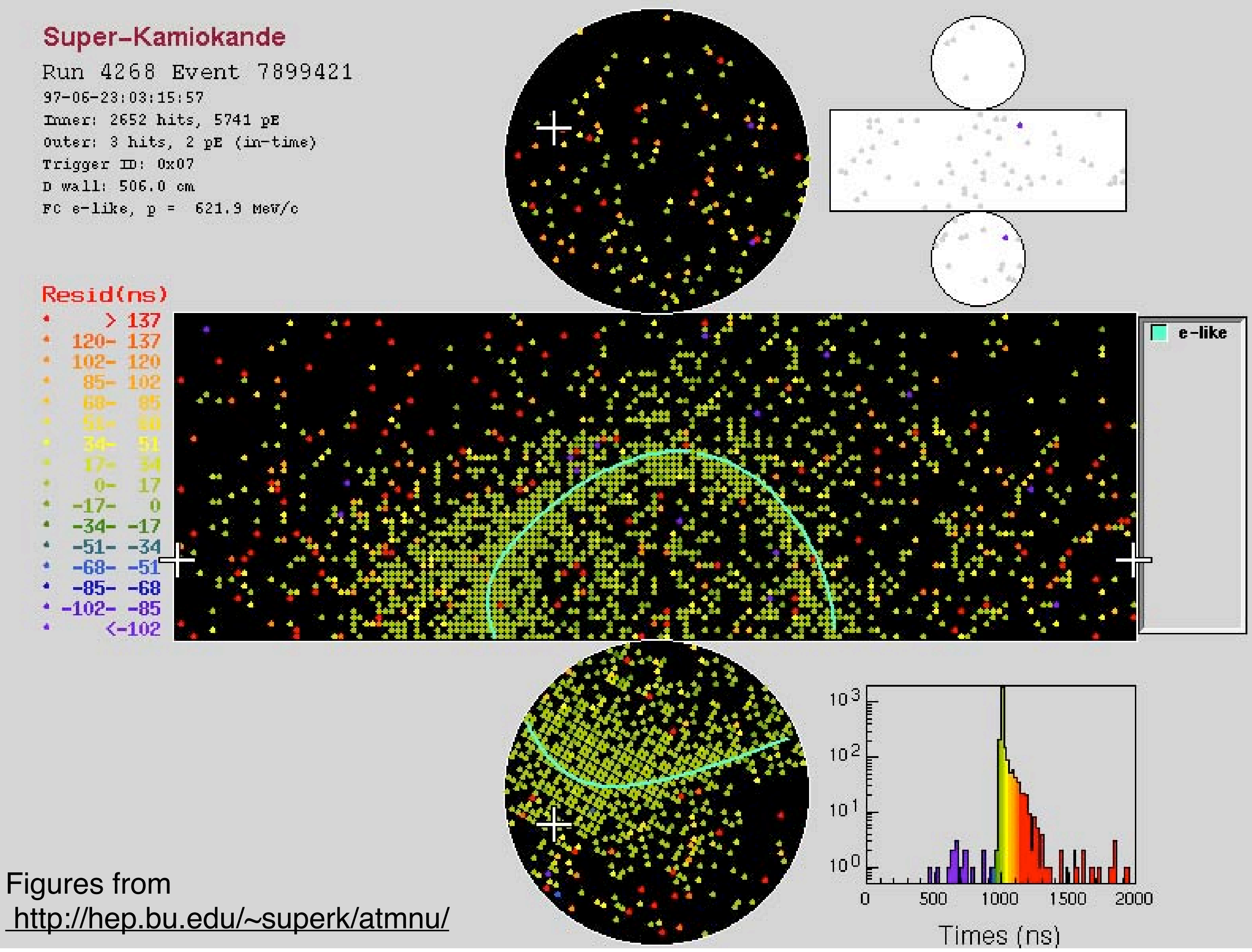
- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.



Figures from M. Earl's PhD Thesis



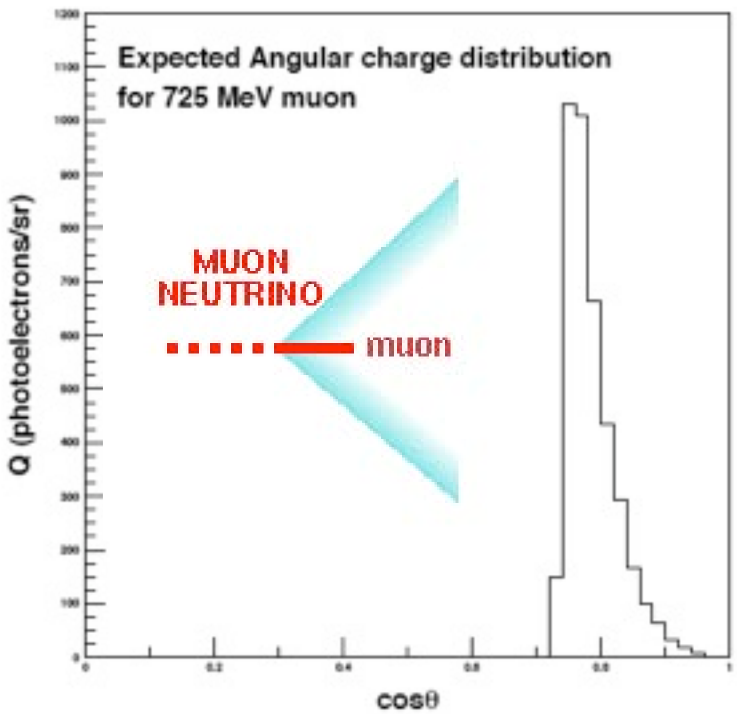
Useful trick: Count decay electrons from π→μ→e decay. Good way to count π's and μ's that are below threshold



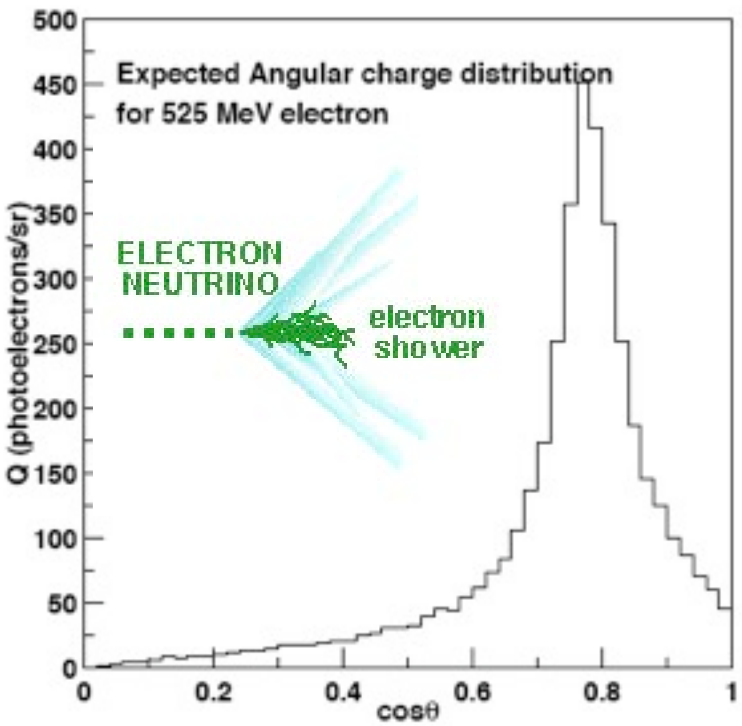
Figures from
http://hep.bu.edu/~superk/atmnu/

Water Cherenkov: e/μ identification

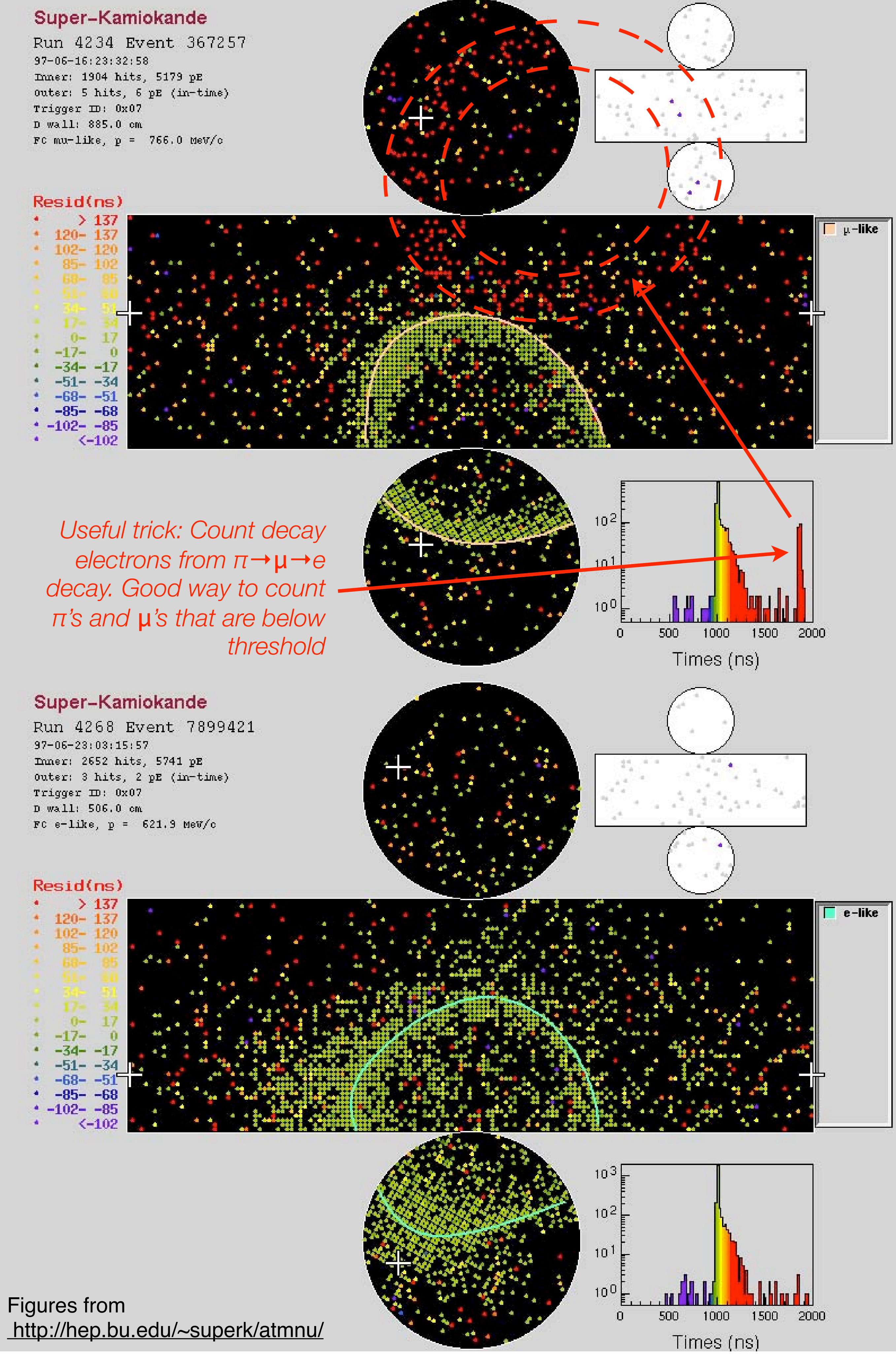
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have “collapsed” rings while electrons are ~always at 42°.



- 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.

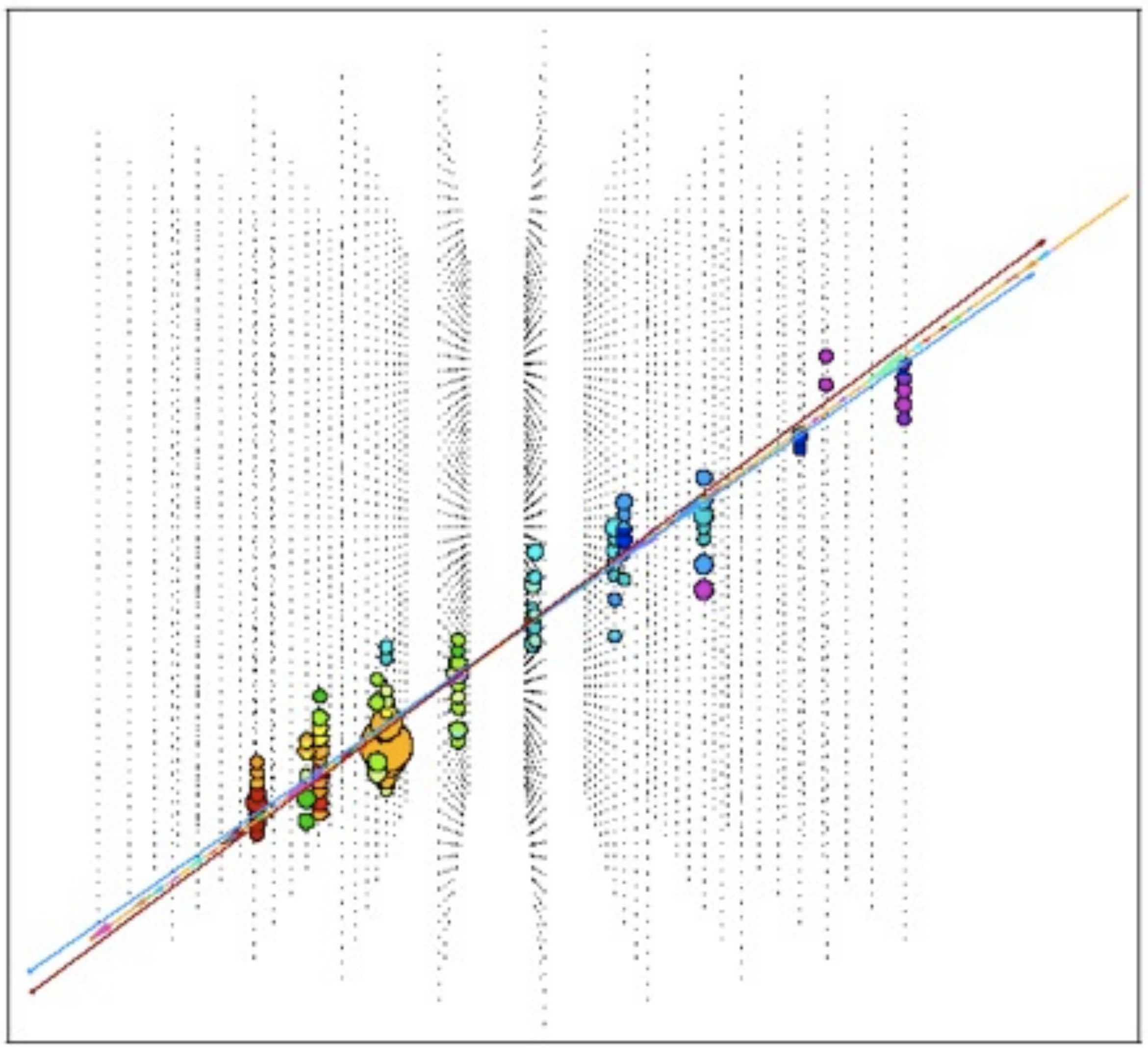


Figures from M. Earl’s PhD Thesis

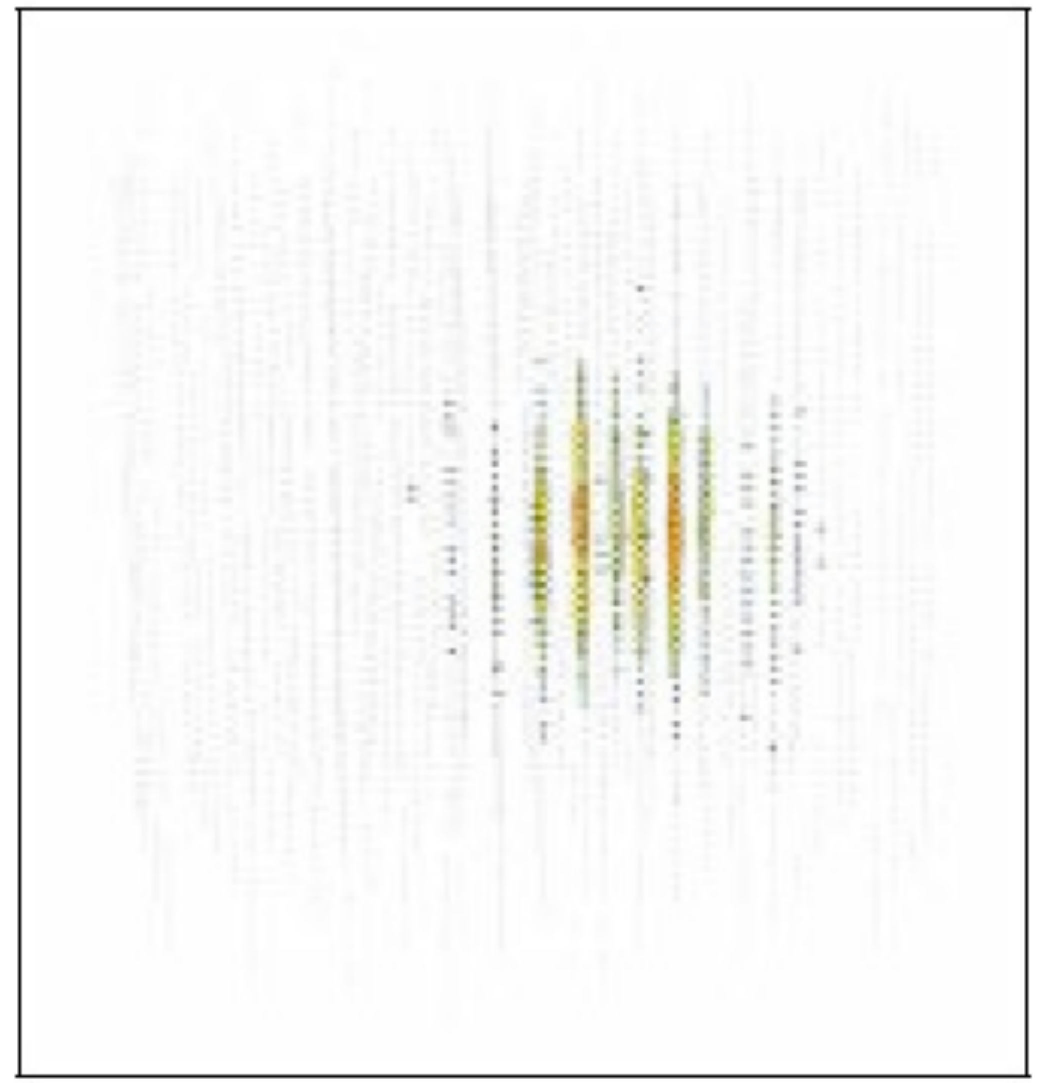


Figures from
http://hep.bu.edu/~superk/atmnu/

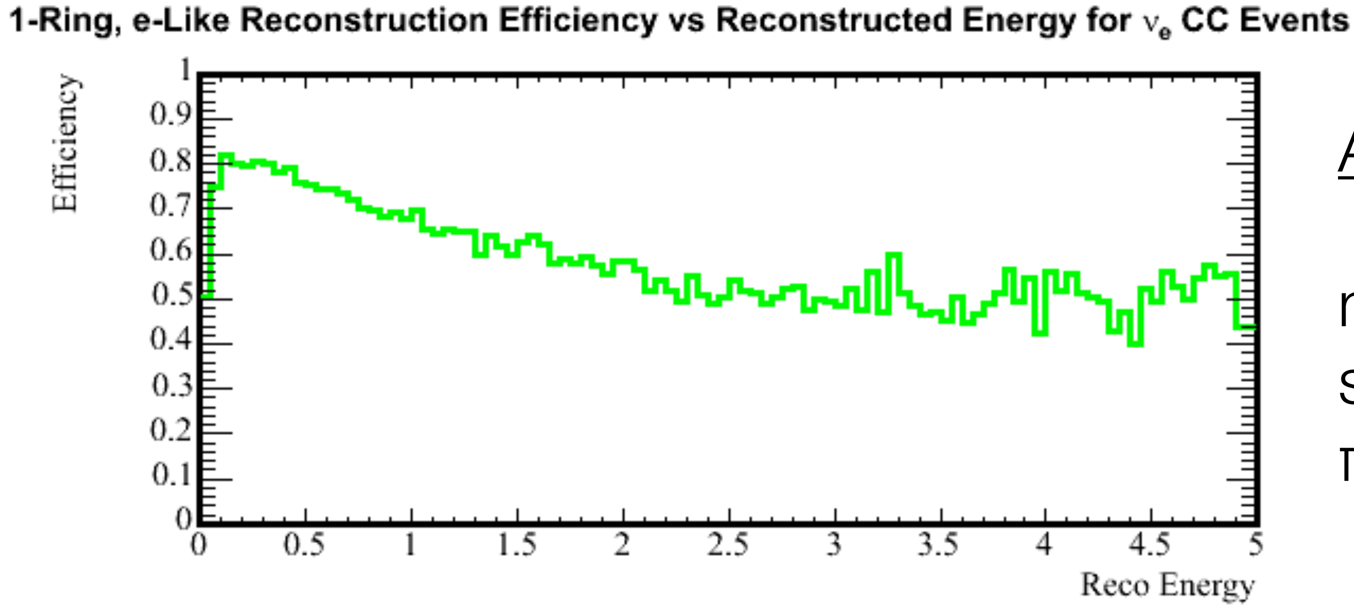
Particle ID in Ice Cube

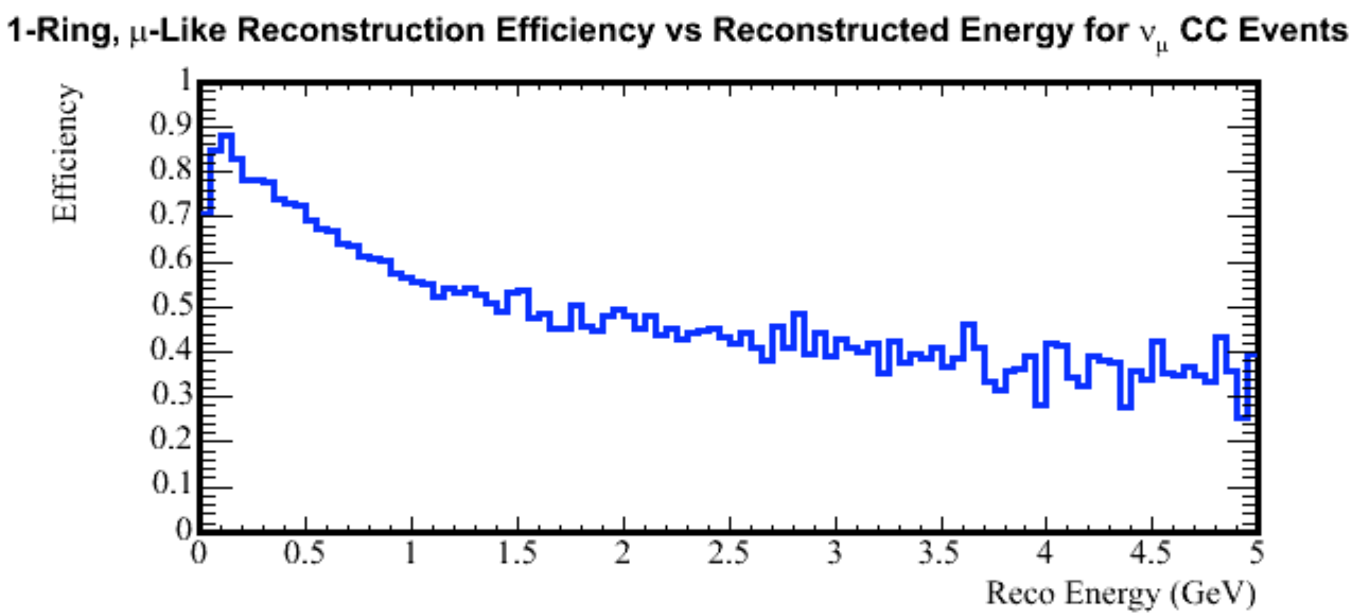


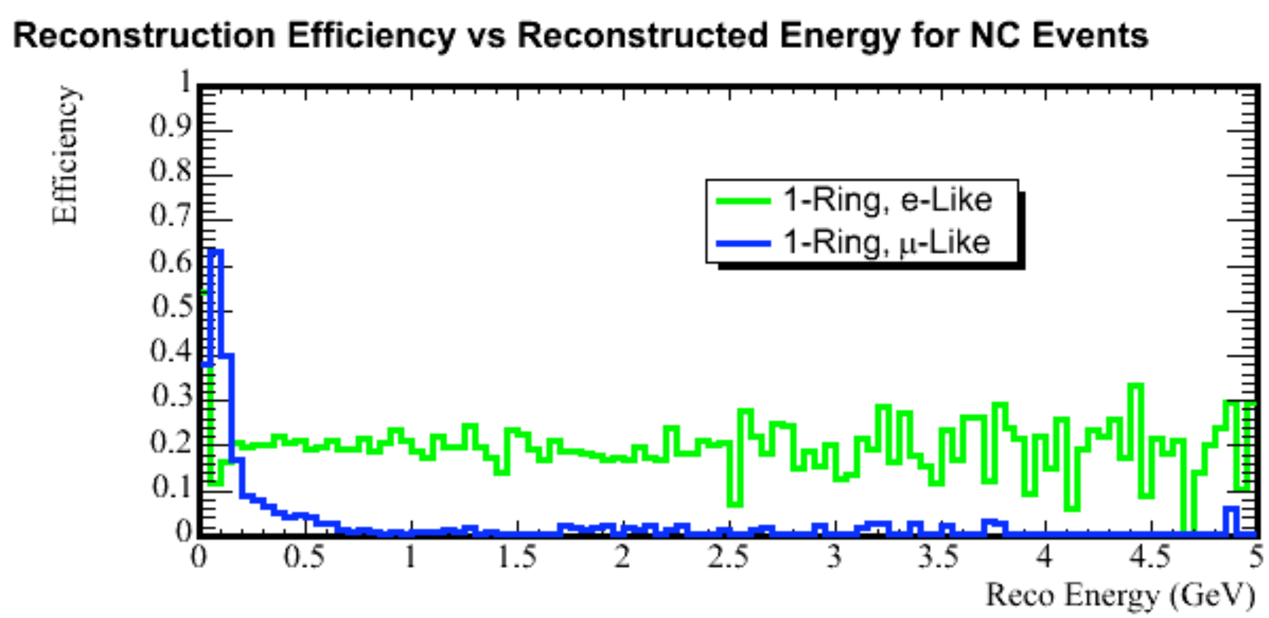
10 TeV muon neutrino induced upward muon



375 TeV electron neutrino





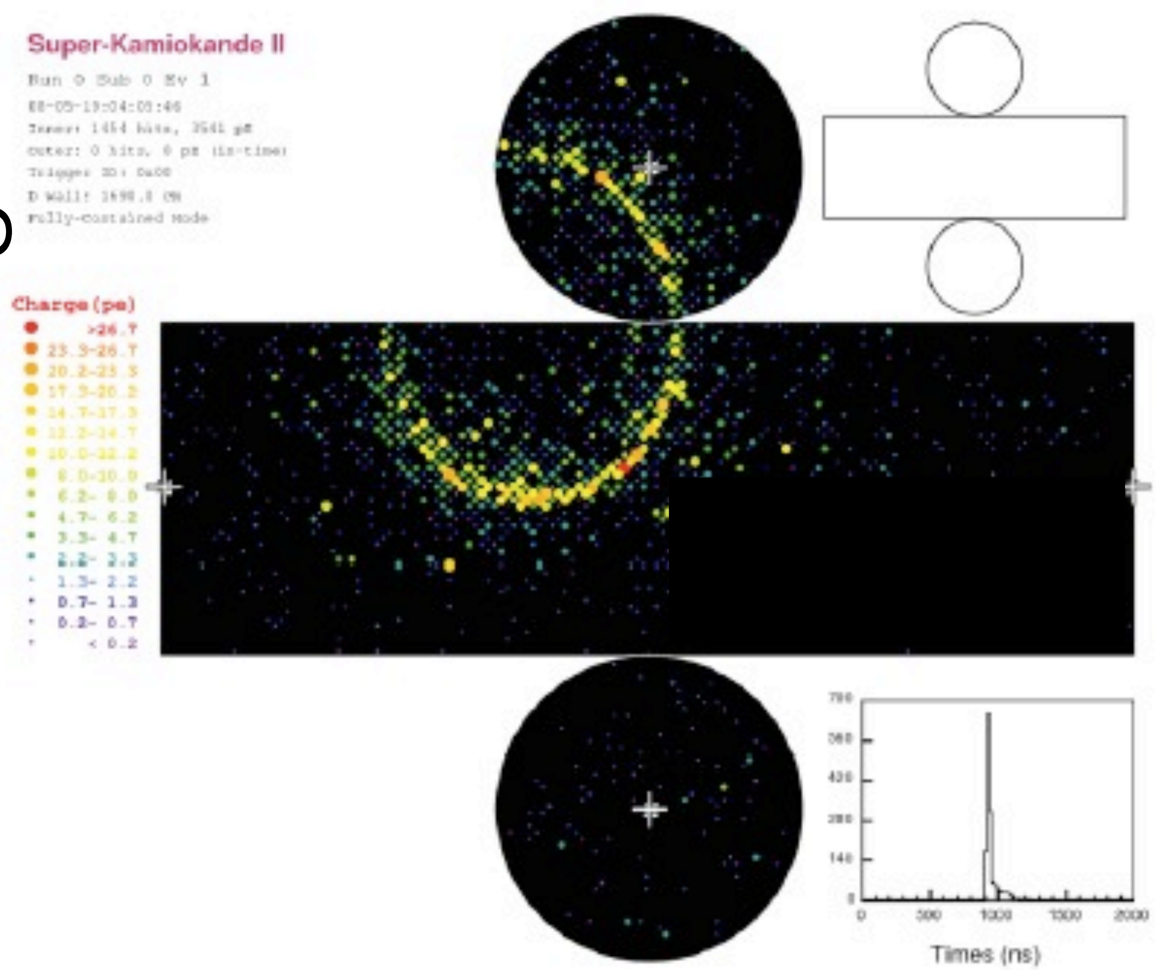


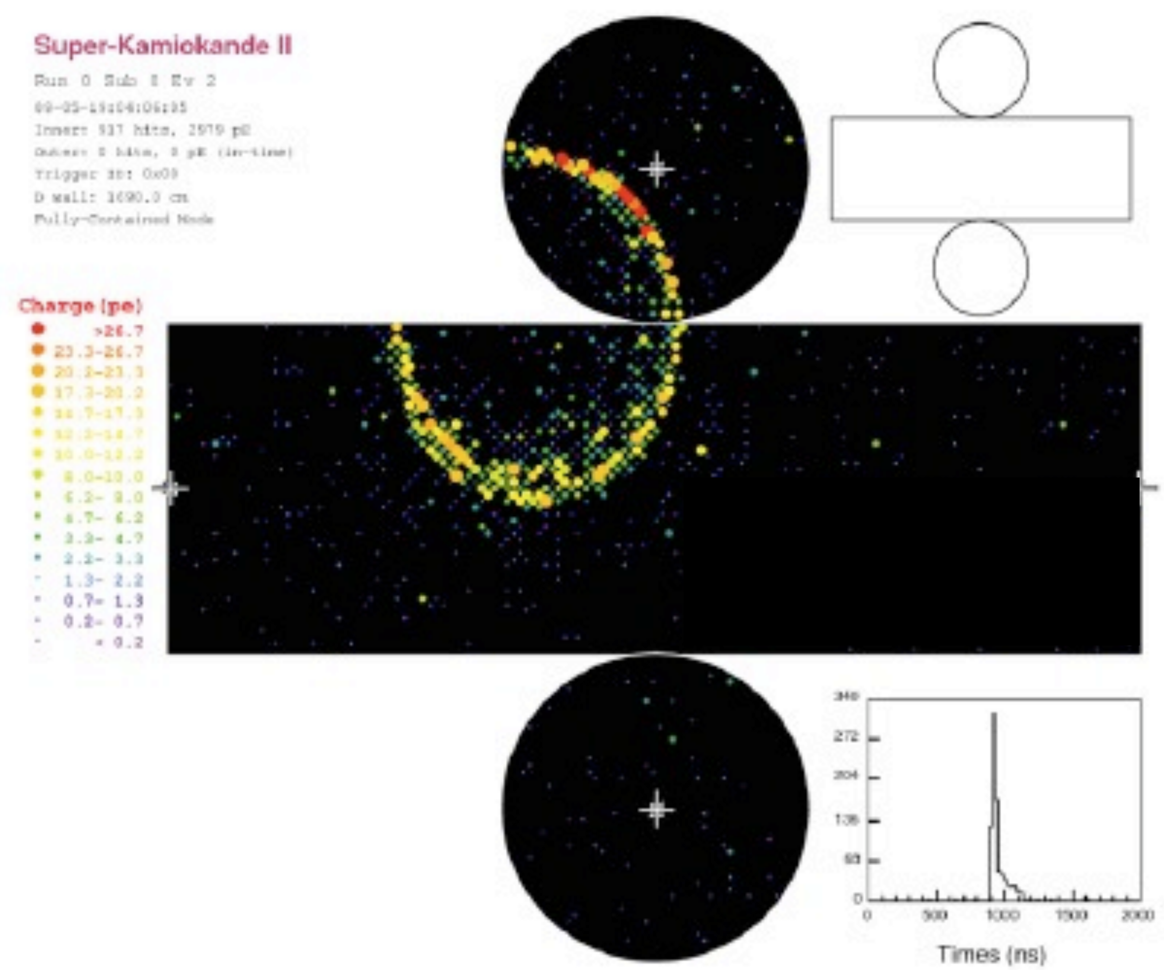
<u>Additional selections:</u>

	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%

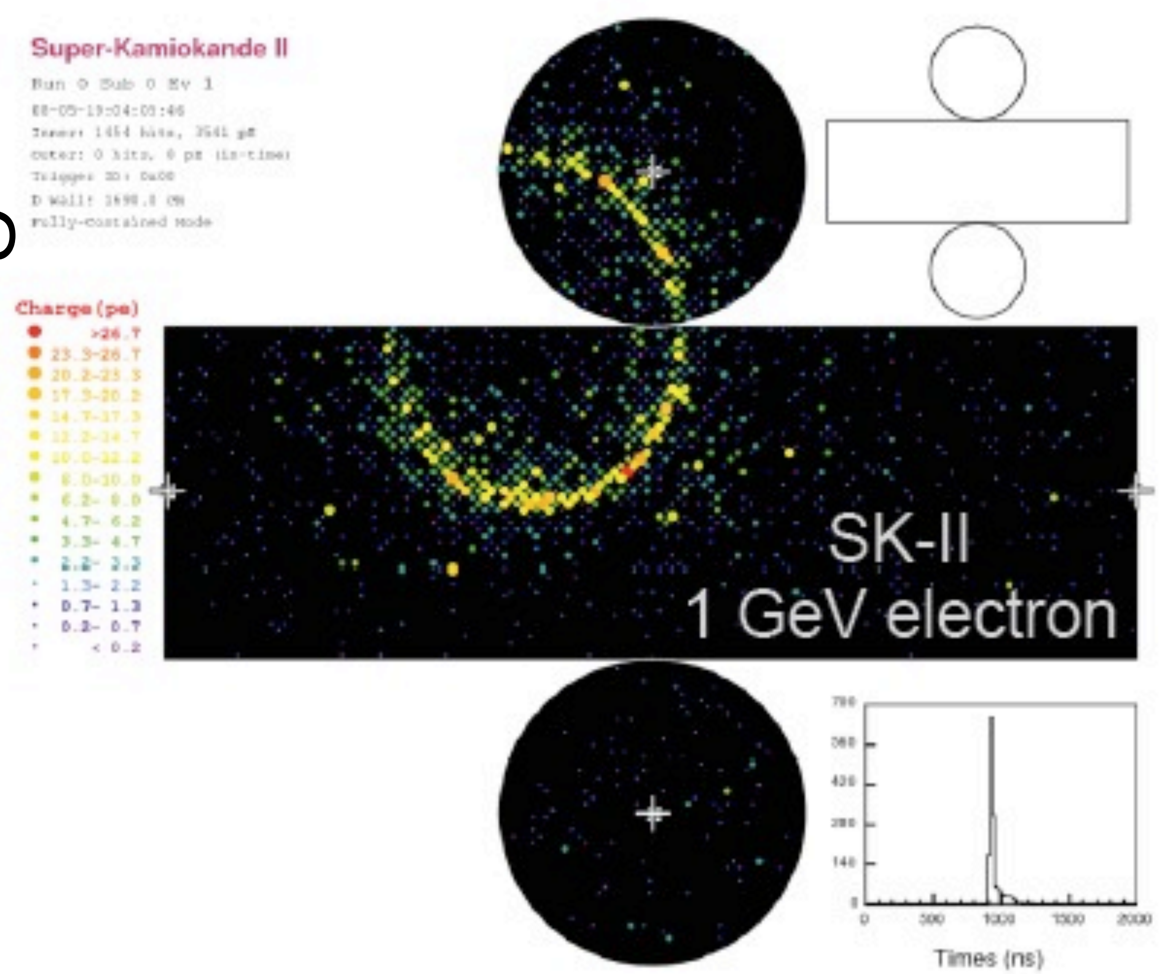
Notice: NC events much more likely to be e-like than **μ**-like due to π^0 production

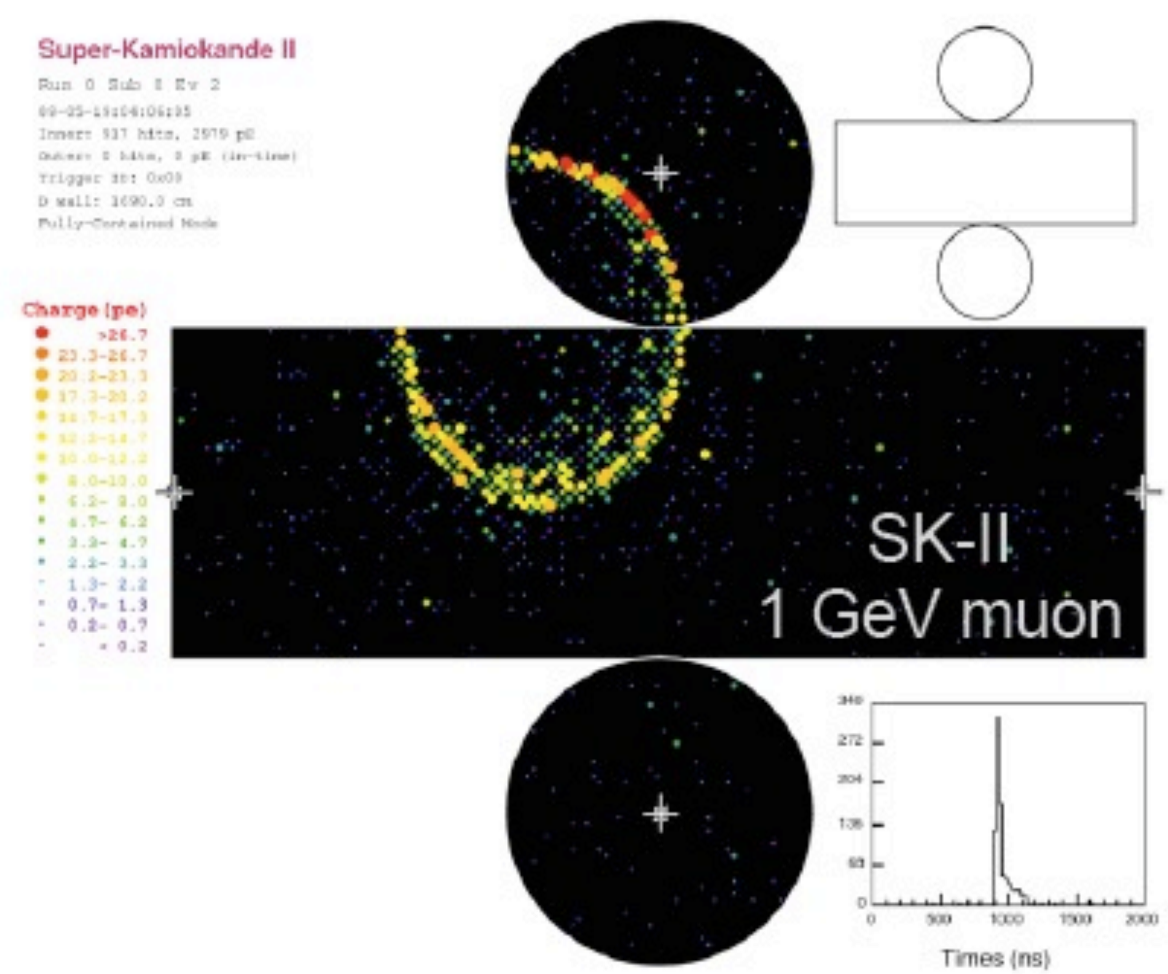
20% coverage


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


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

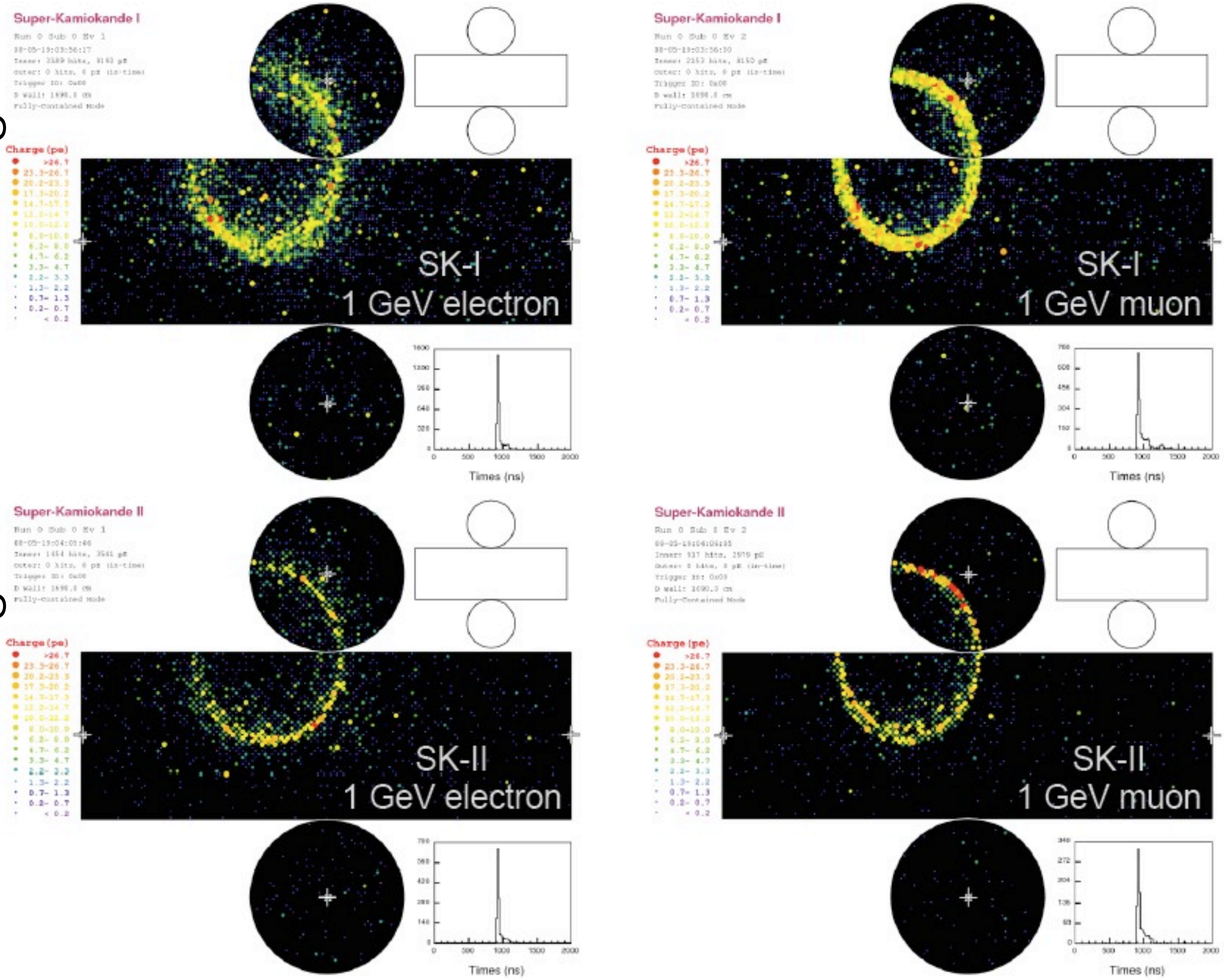
20% coverage


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

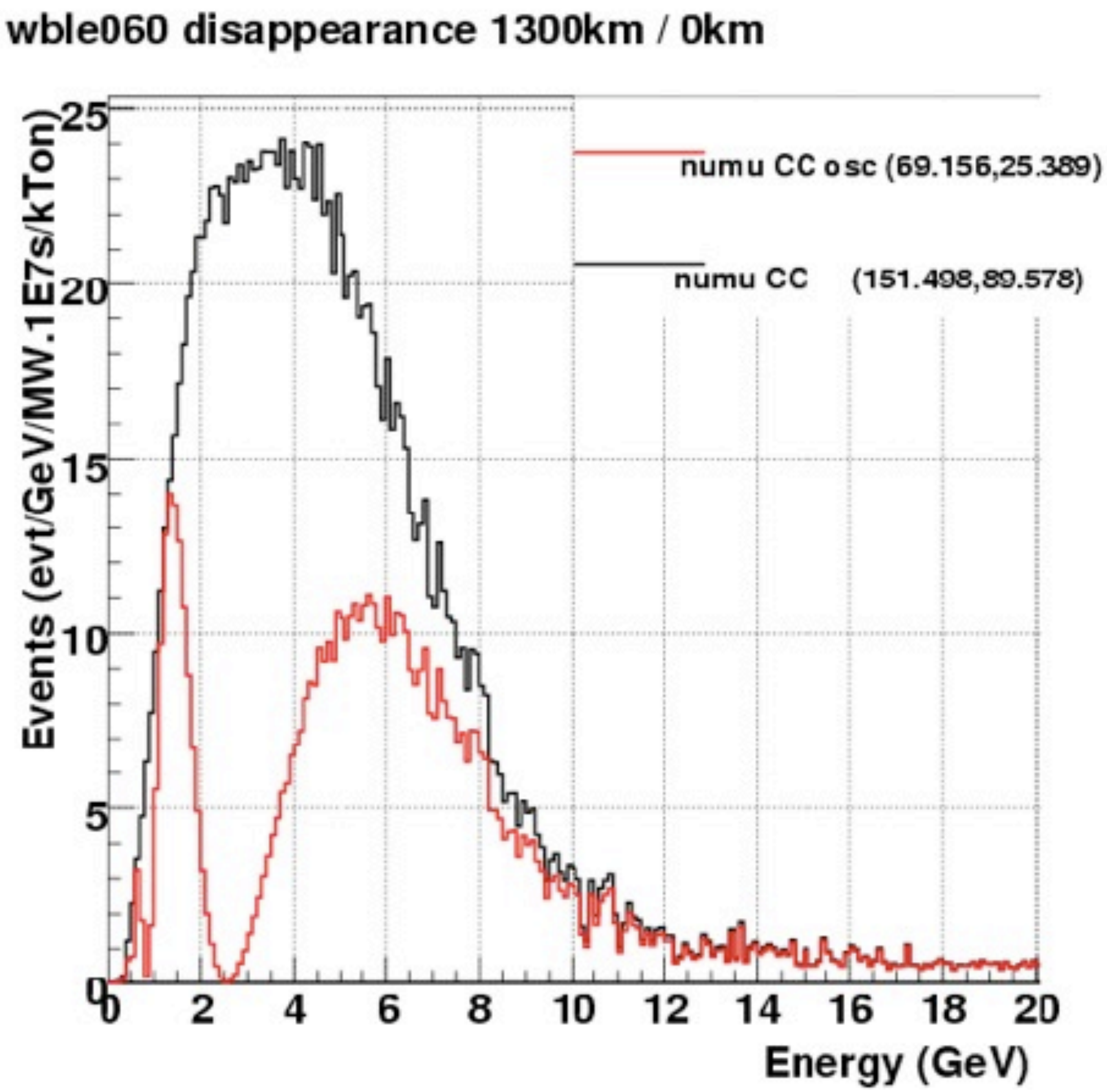

Super-Kamiokande II
Charge (pe)
SK-II
1 GeV muon
Times (ns)

40% coverage

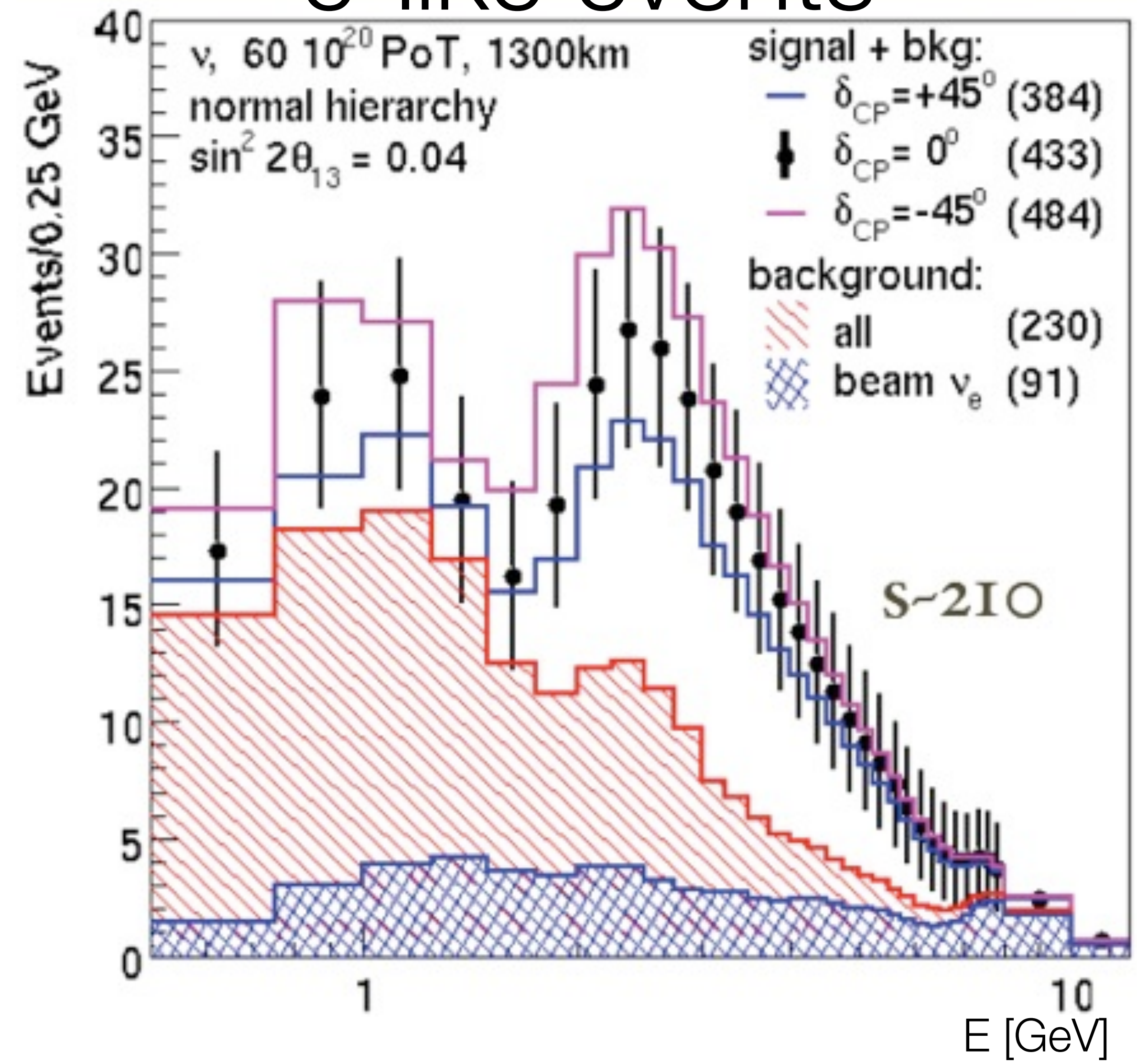
20% coverage



Pushing the technology: Sub-GeV to Multi-GeV



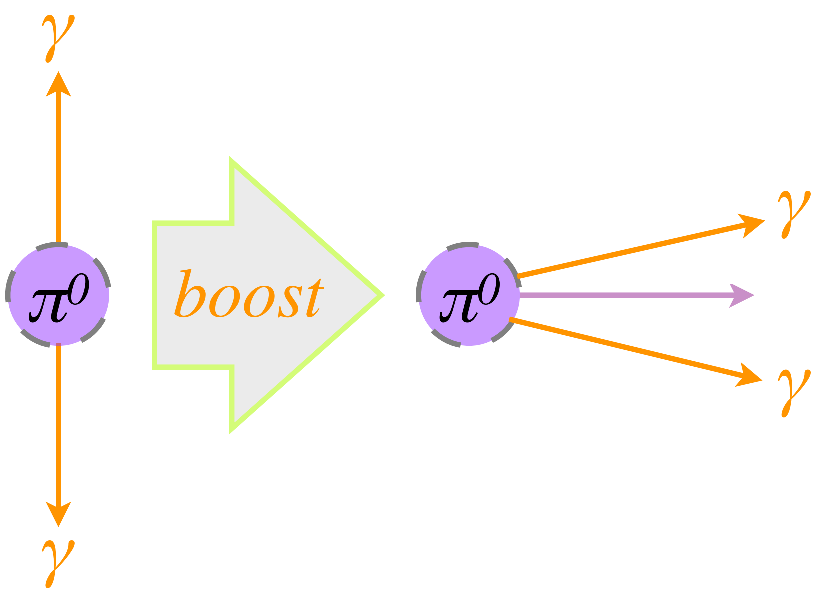
e-like events

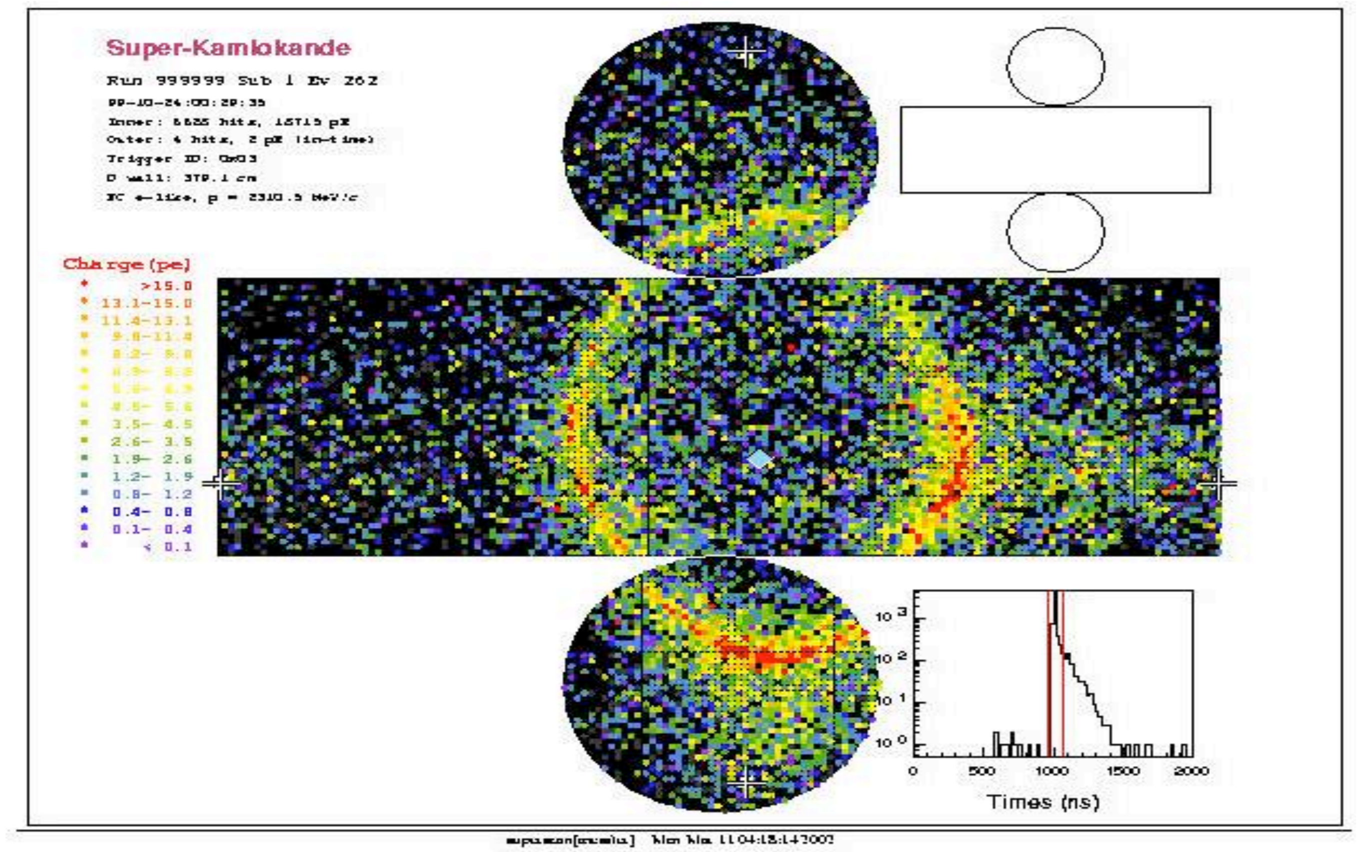


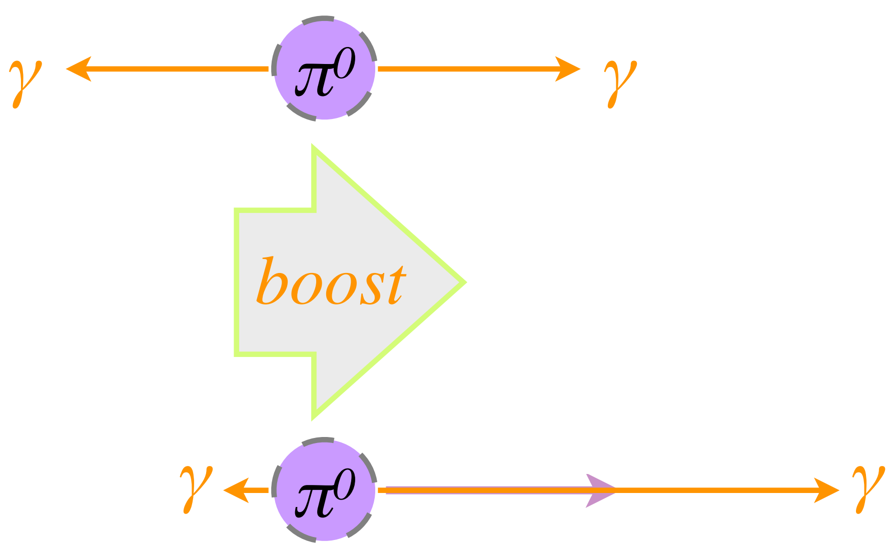
100 kt water detector in multi-GeV 2 MW wide band beam Fermilab to Homestake

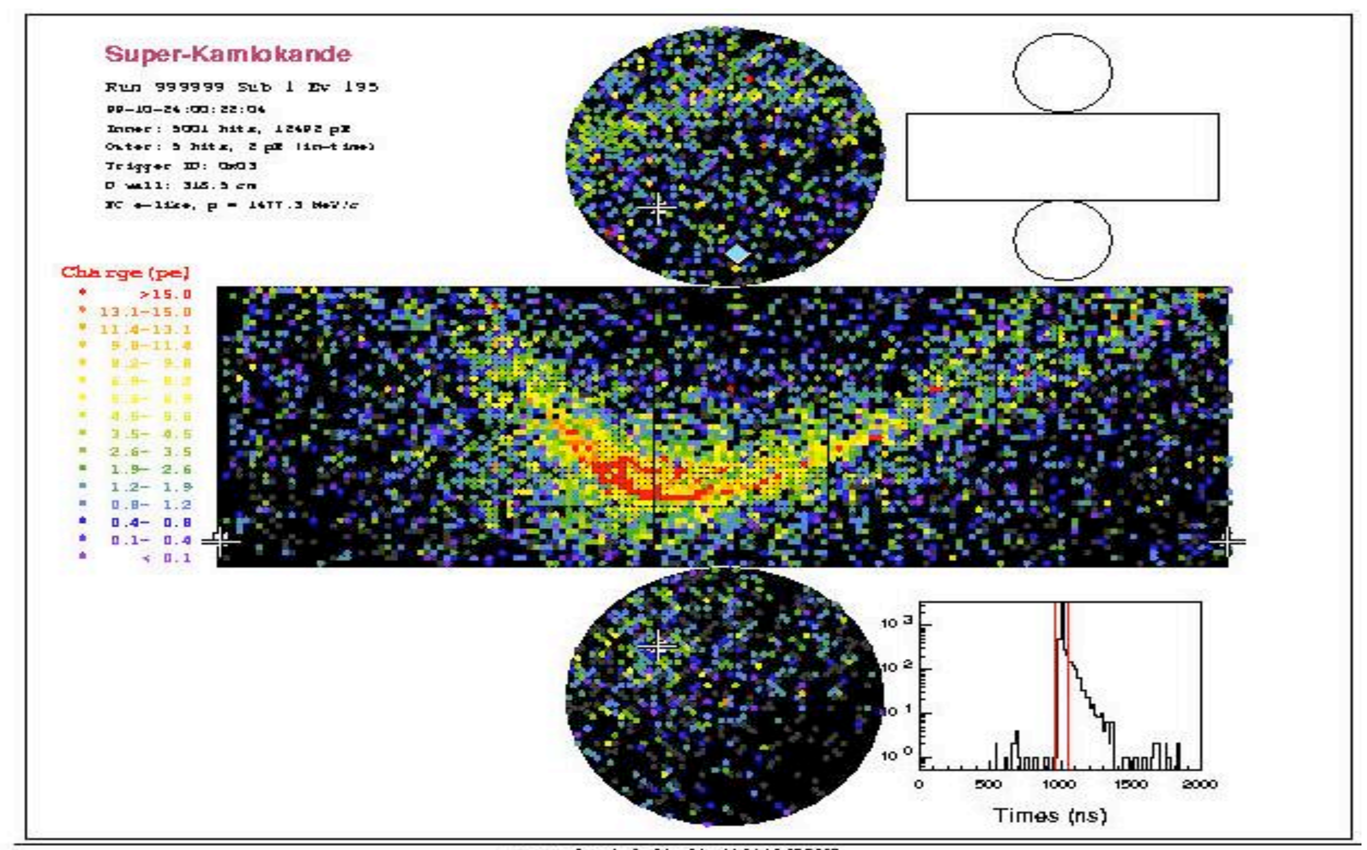
2 GeV visible energy
One is signal, the other background

π^0 decay at high energy



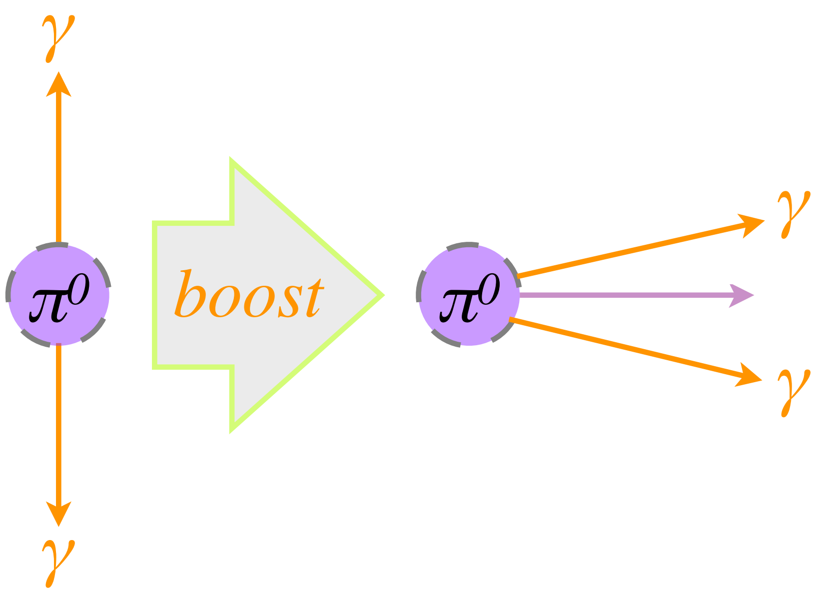


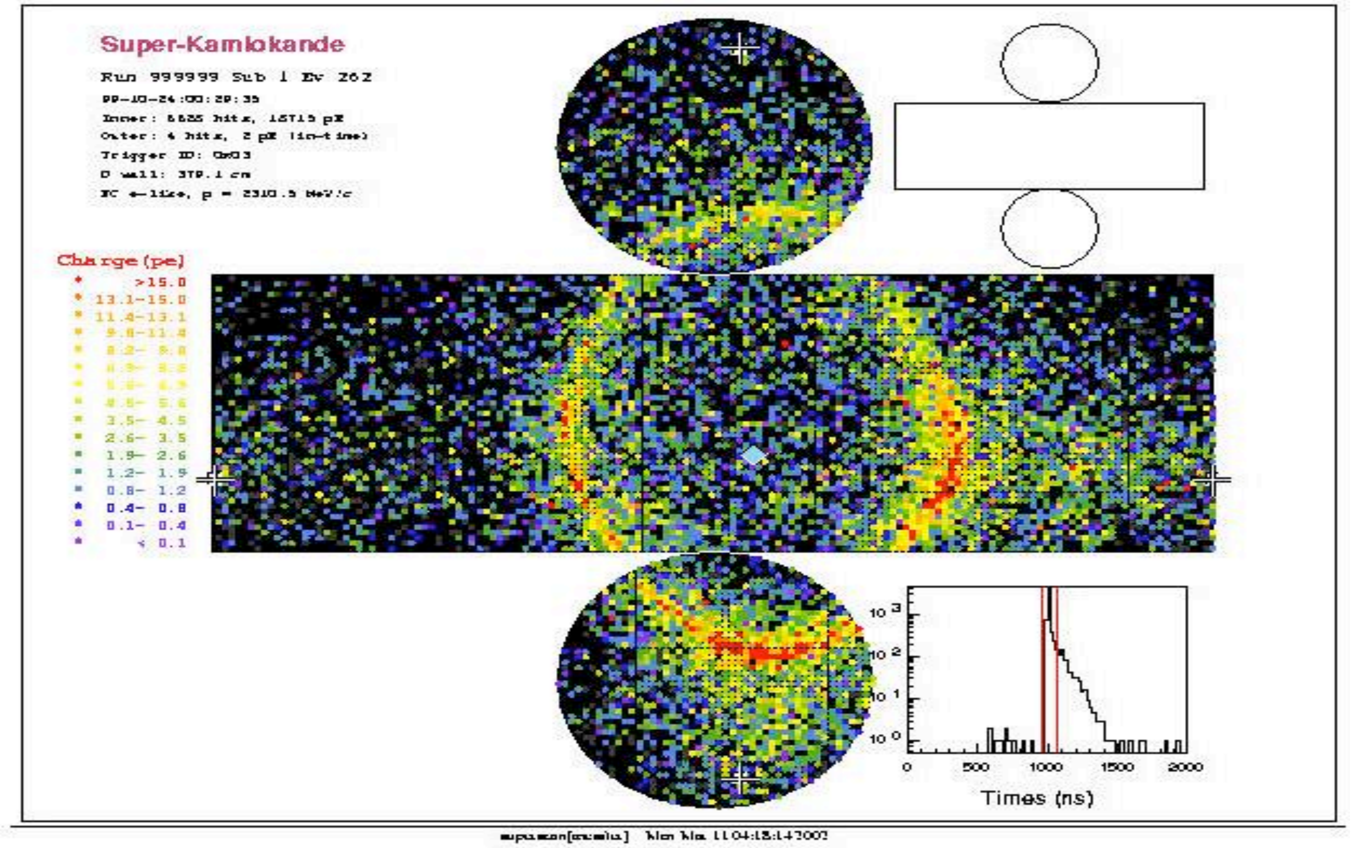




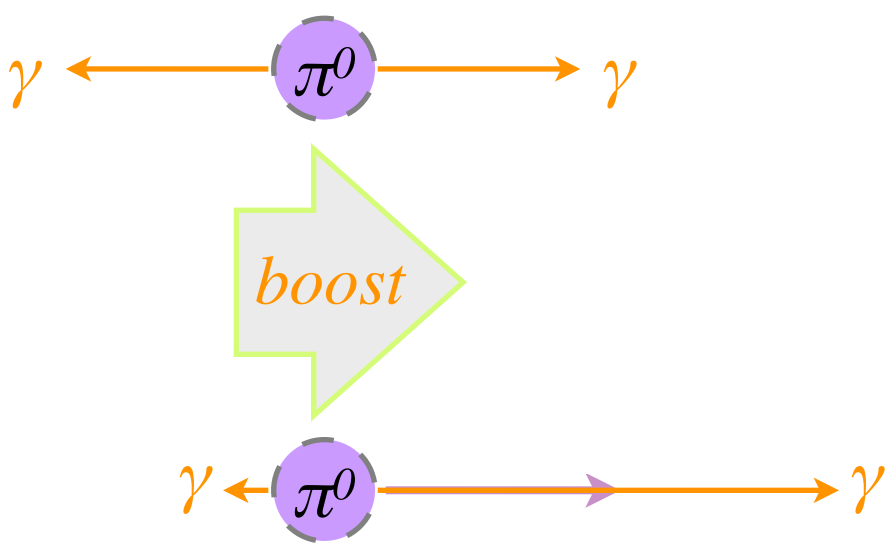
2 GeV visible energy
One is signal, the other background

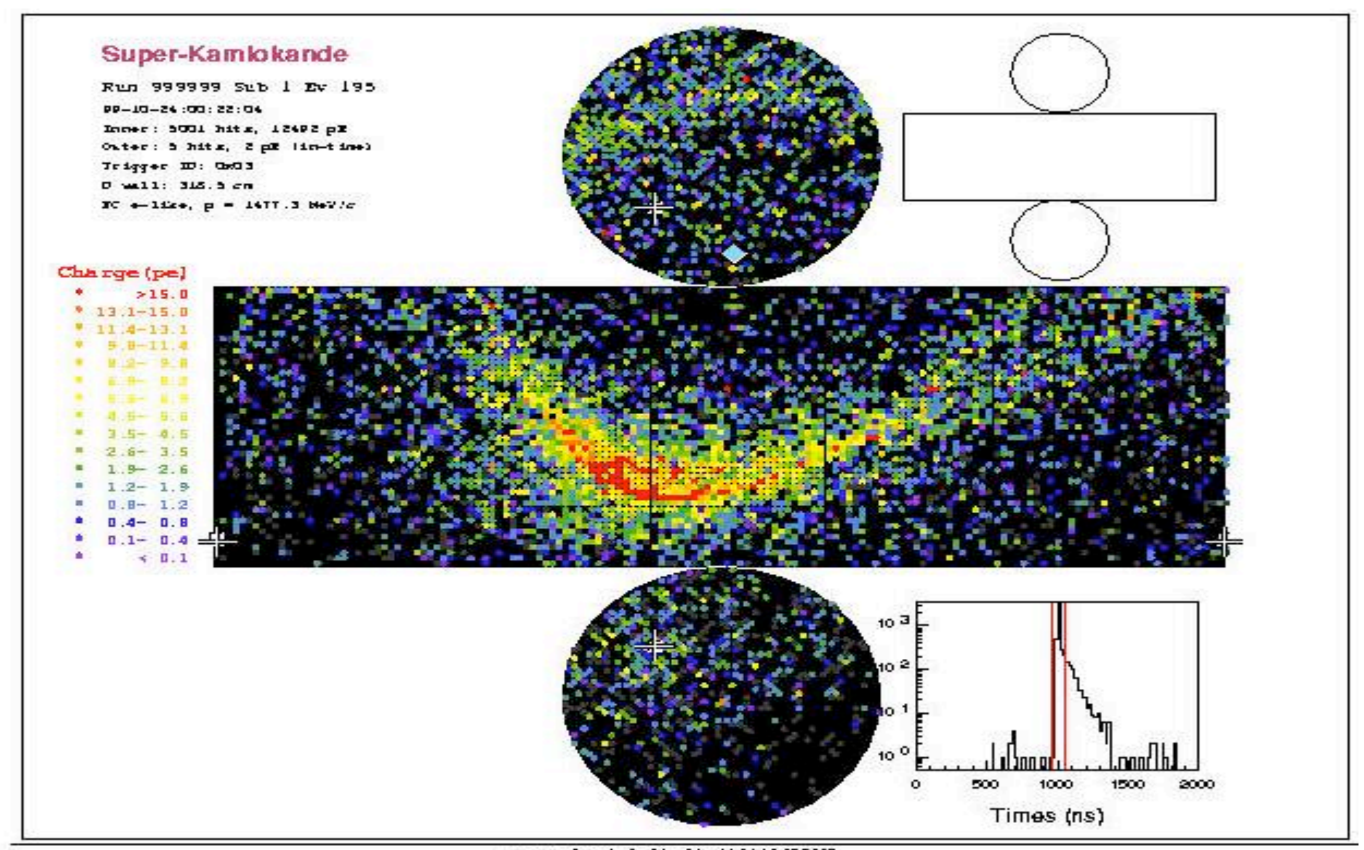
π^0 decay at high energy





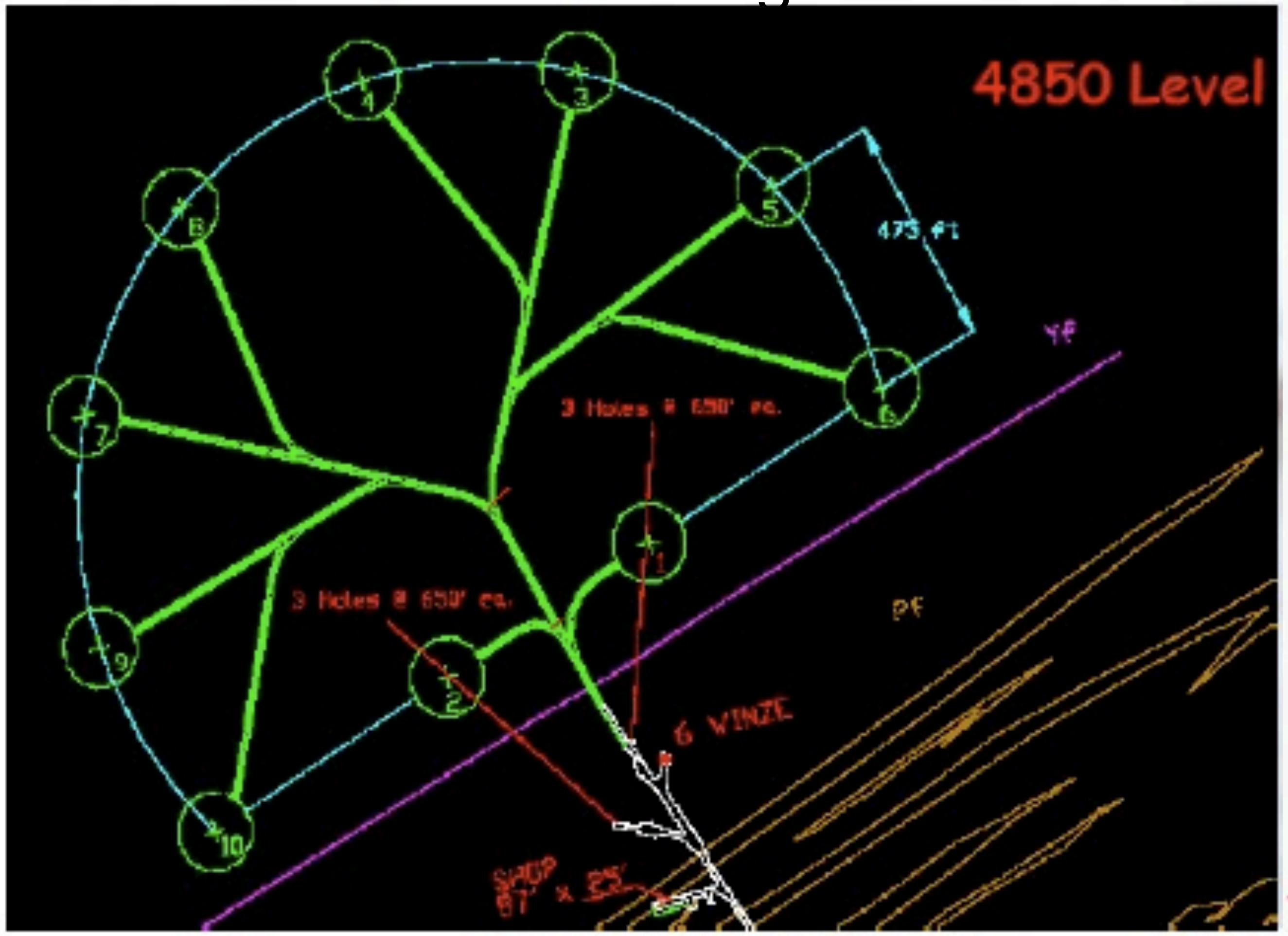
ν_e CC



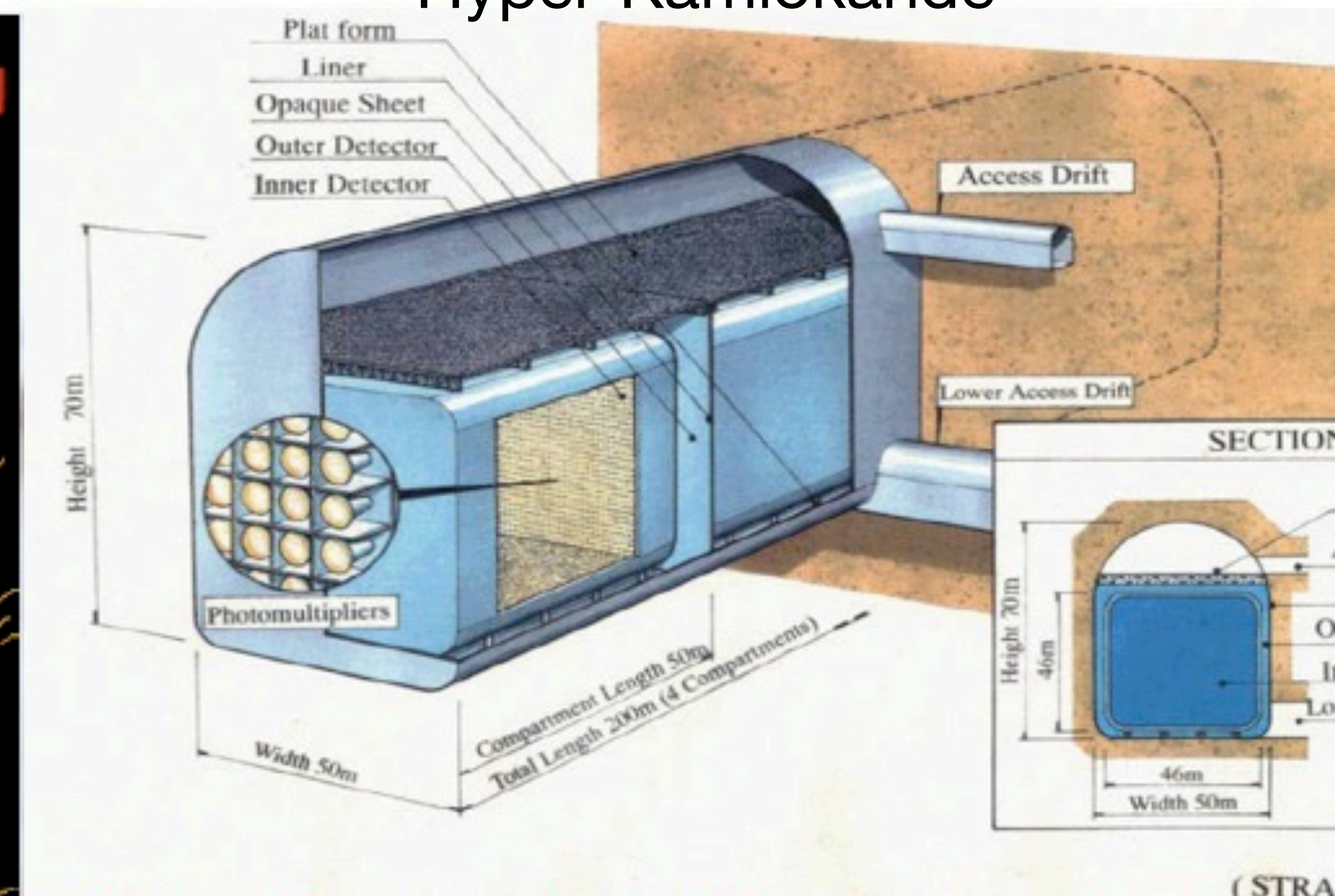


NC π^0

US DUSSEL Underground lab

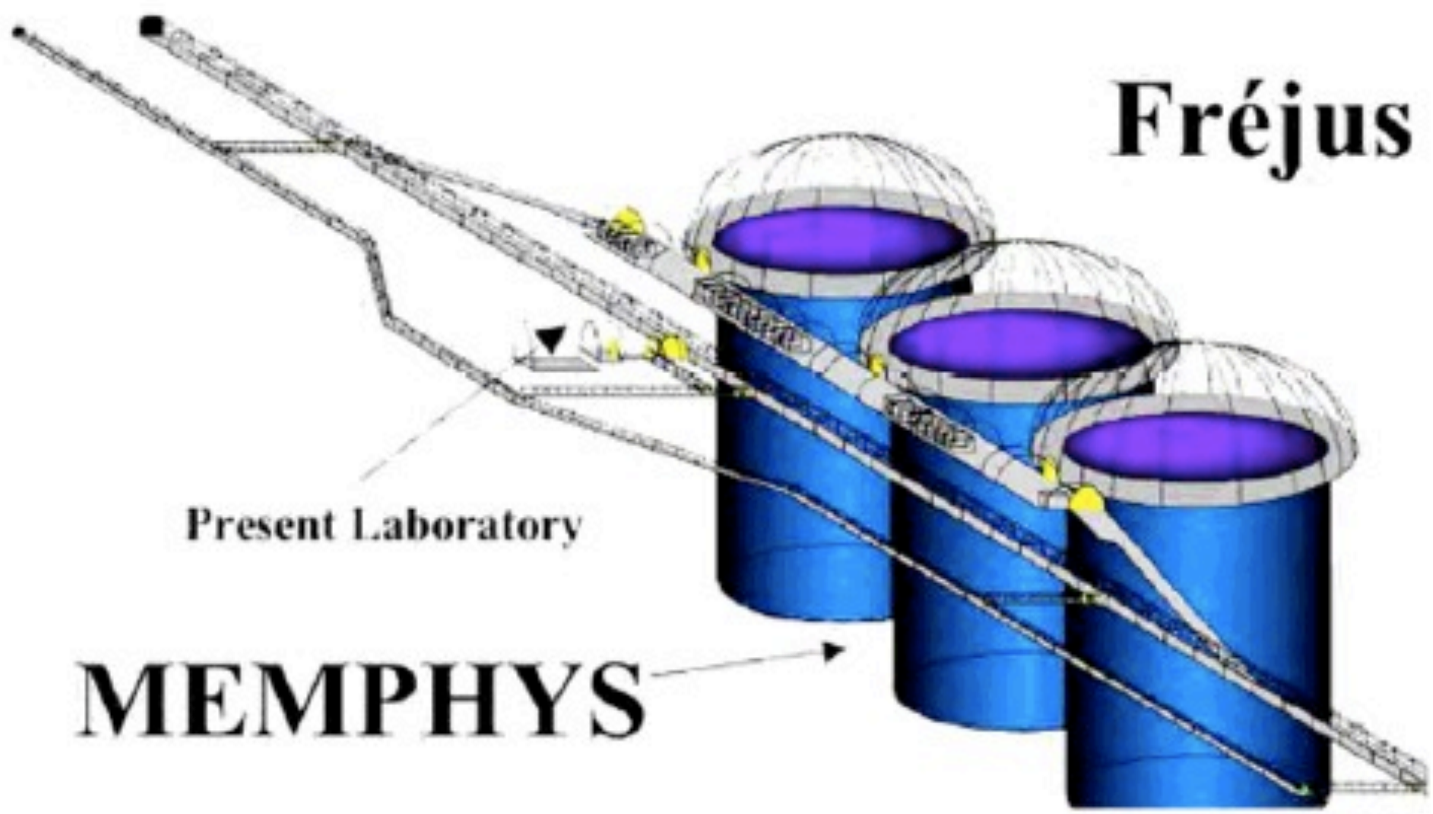


Hyper-Kamiokande



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

Megaton Scale Water Cherenkov Detectors



20% or 40% Photocathode coverage?

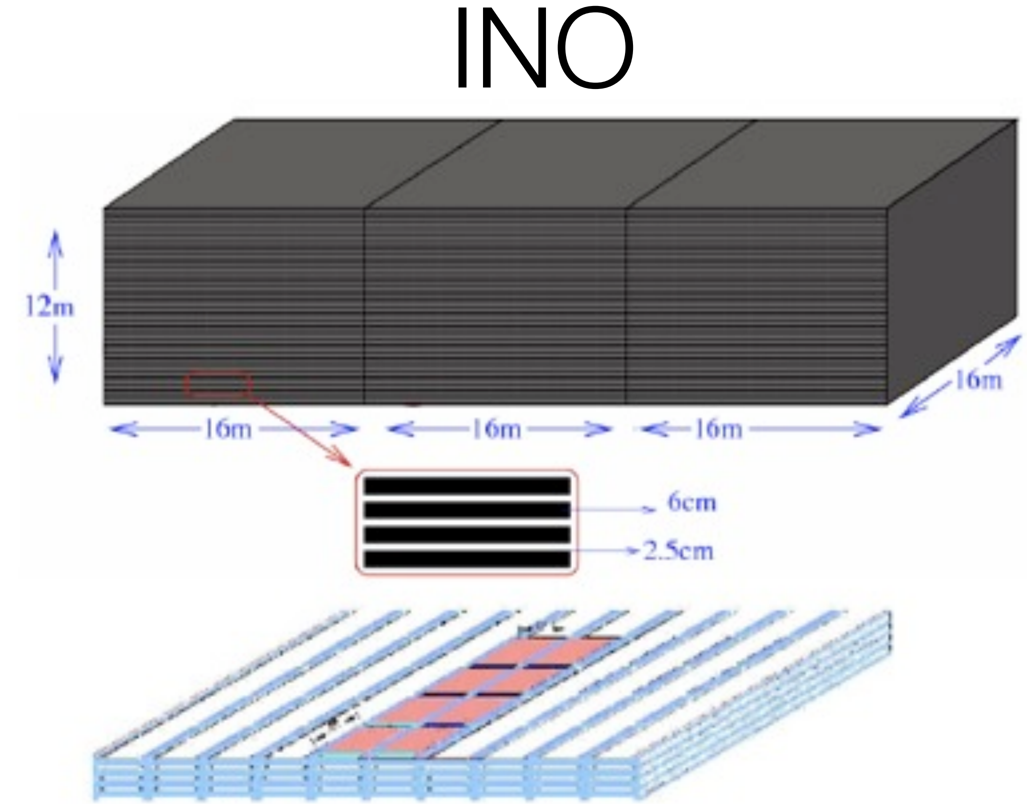
PMT's cost ~$3K USD and are one of the schedule drivers for construction of very large water Cherenkov detectors. Can you live with fewer?

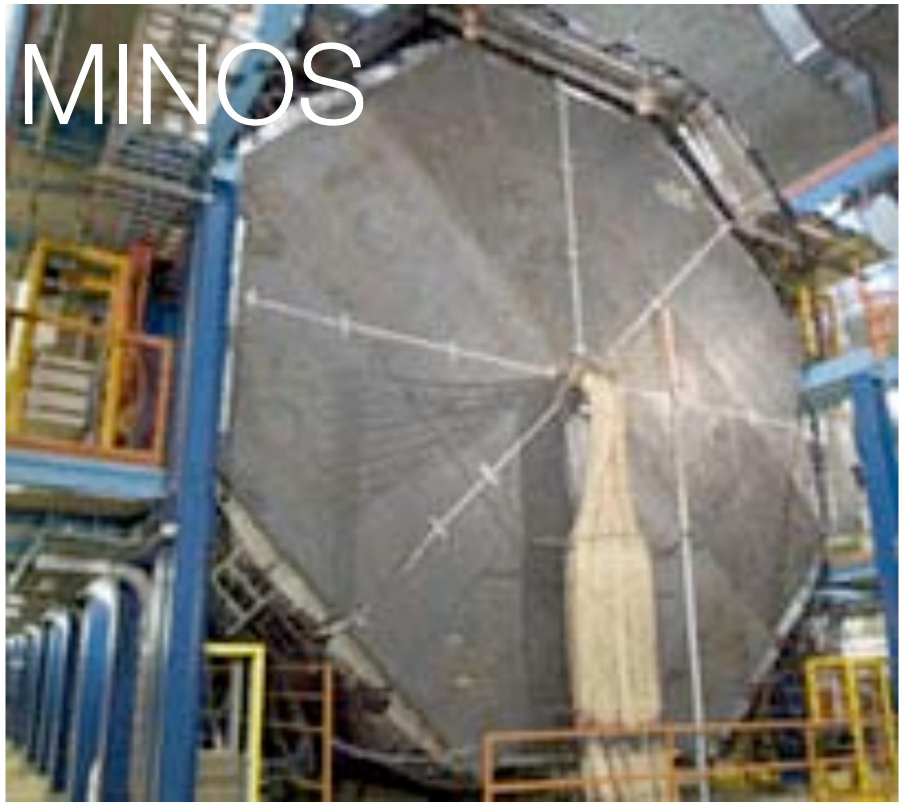
	Super-K I (40% coverage)	Super-K II (20% coverage)
Sub-GeV vertex resolution	26 cm (e-like) / 23 cm (μ-like)	30 cm (e-like) / 29 cm (μ-like)
Sub-GeV particle mis-ID	0.81% (e-like) / 0.70% (μ-like)	0.69% (e-like) / 0.96% (μ-like)
Sub-GeV momentum resolution	4.8% (e-like) / 2.5% (μ-like)	6.3% (e-like) / 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 CCν_e likelihood effic.	83.7% (±0.1% stat)	84.8 %
T2K BG likelihood effic.	21.3 %	21.5 %

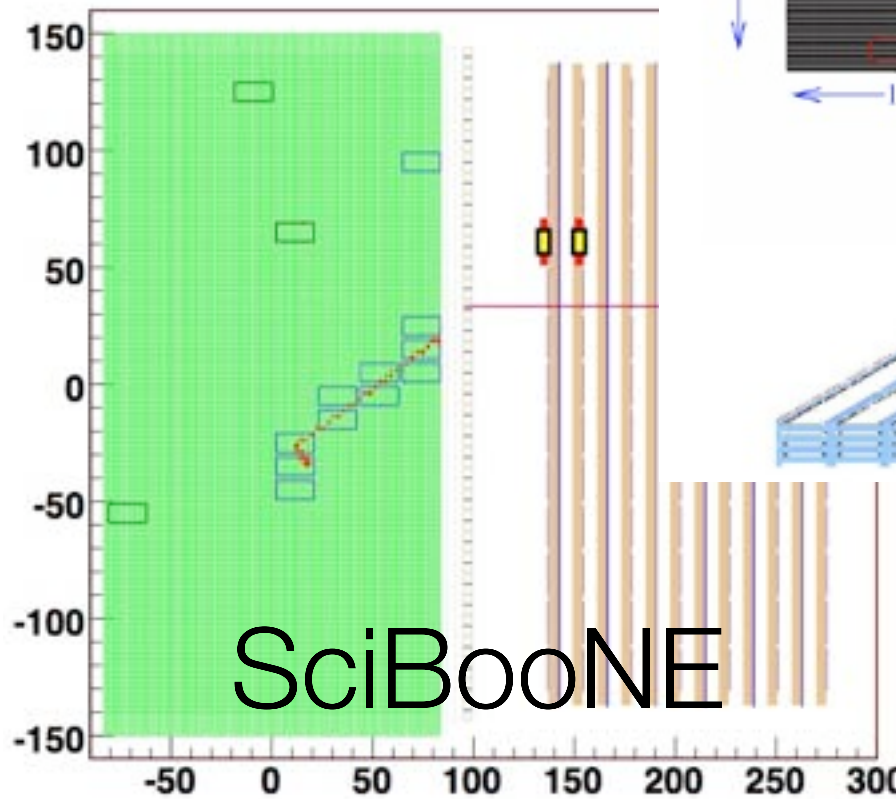
S.T. Clark, Ph.D. Thesis (2006)
F. Dufour, T2KK Workshop (2006)

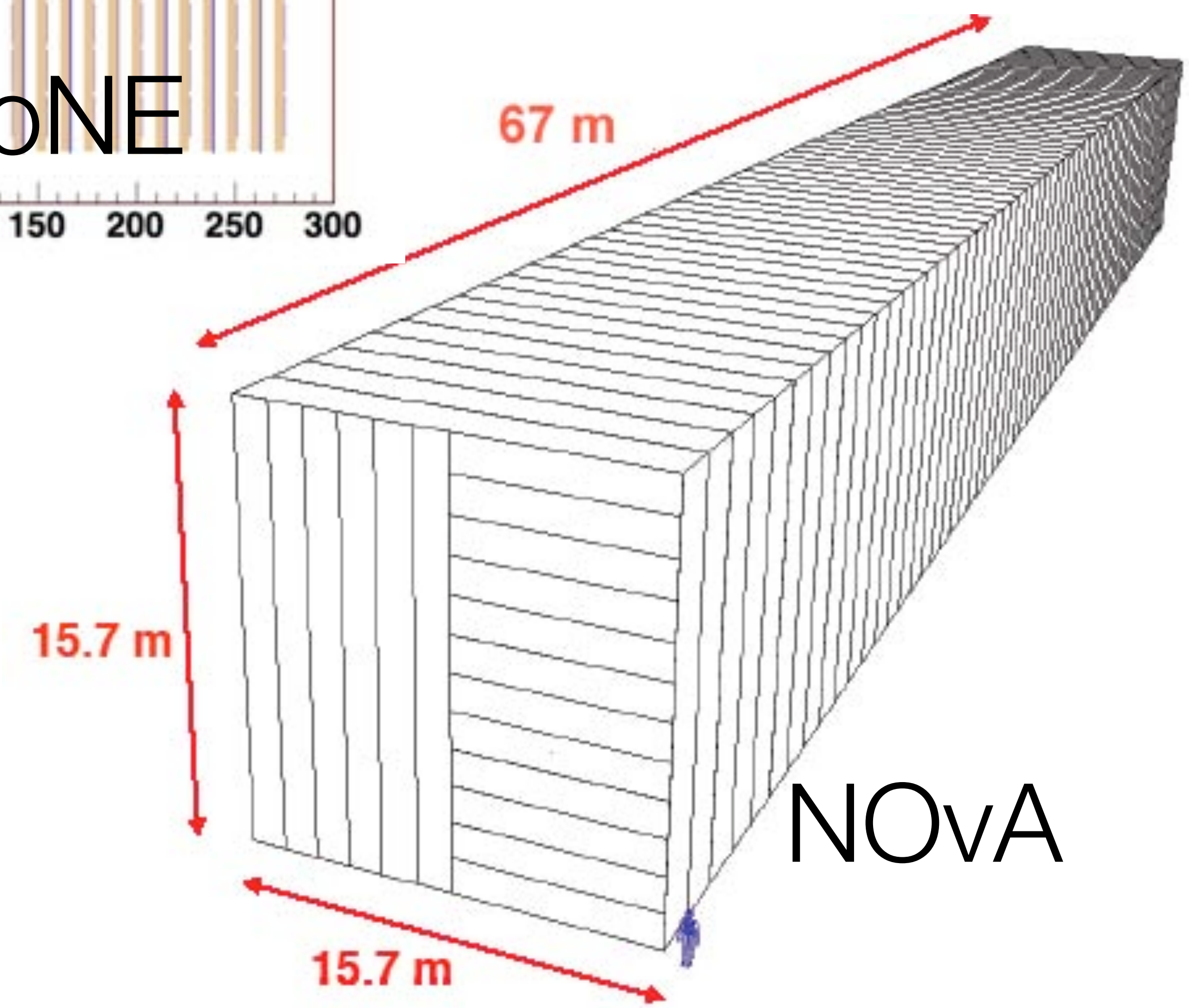
<u>Preliminary</u> numbers, for comparison purposes.
Final published efficiencies and BG may differ.

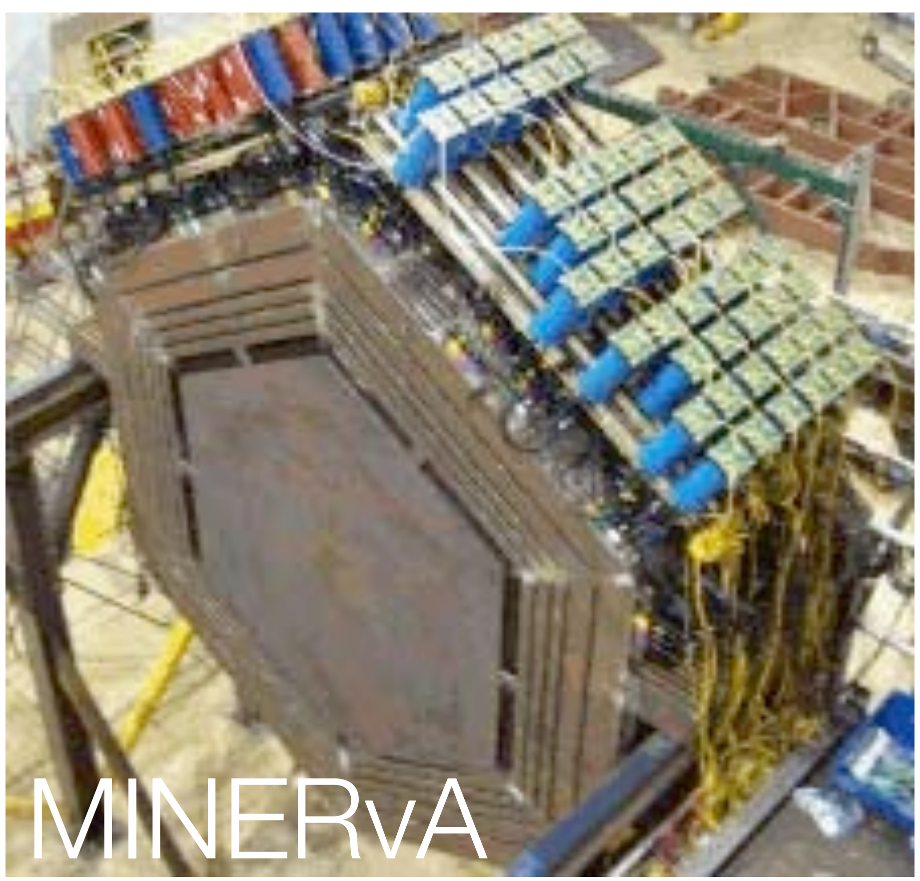
Tracking calorimeters







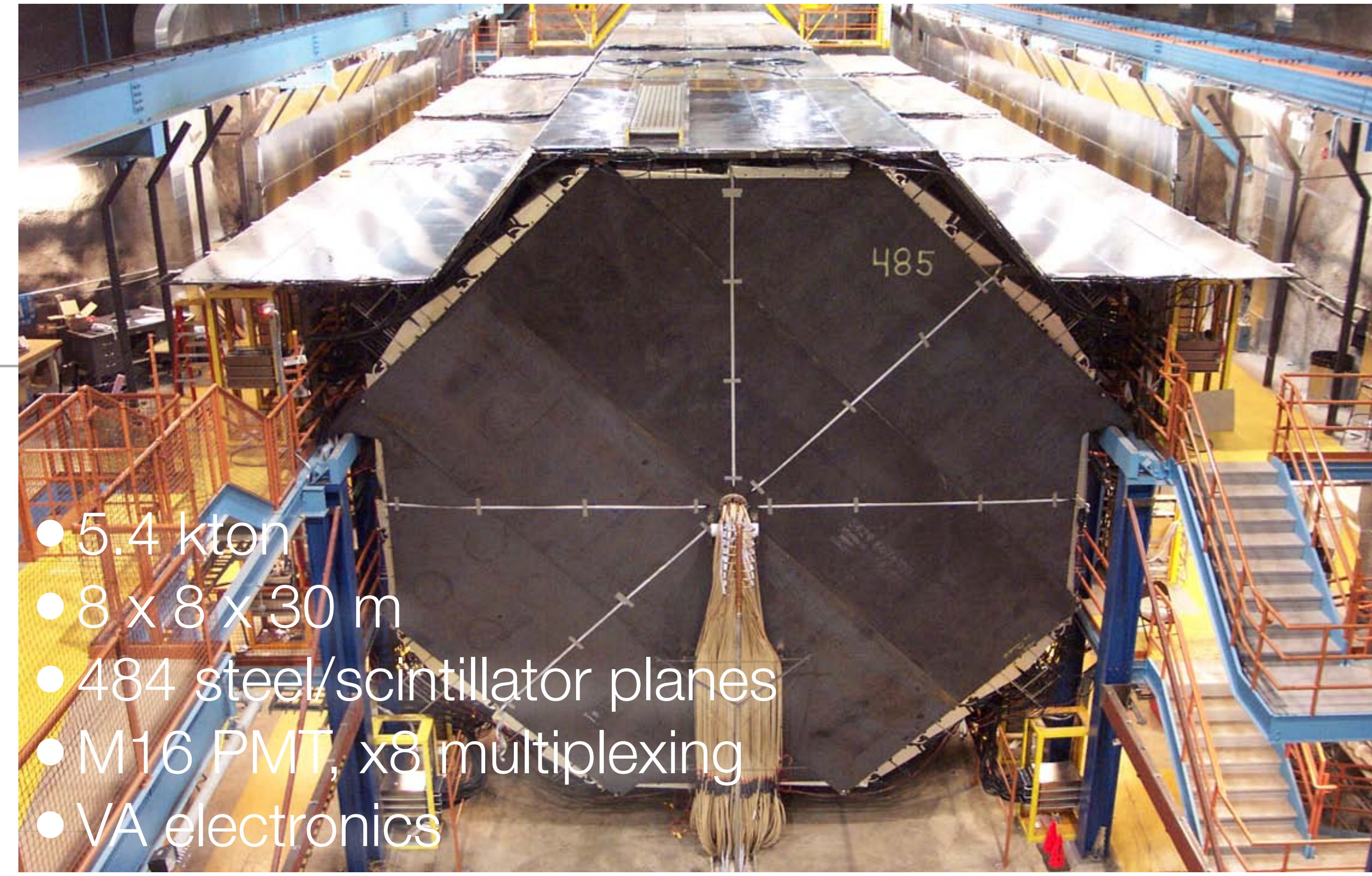


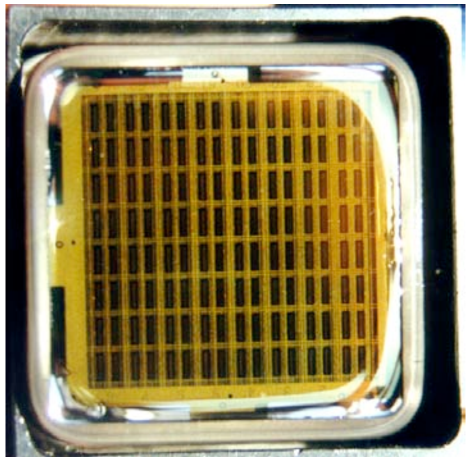


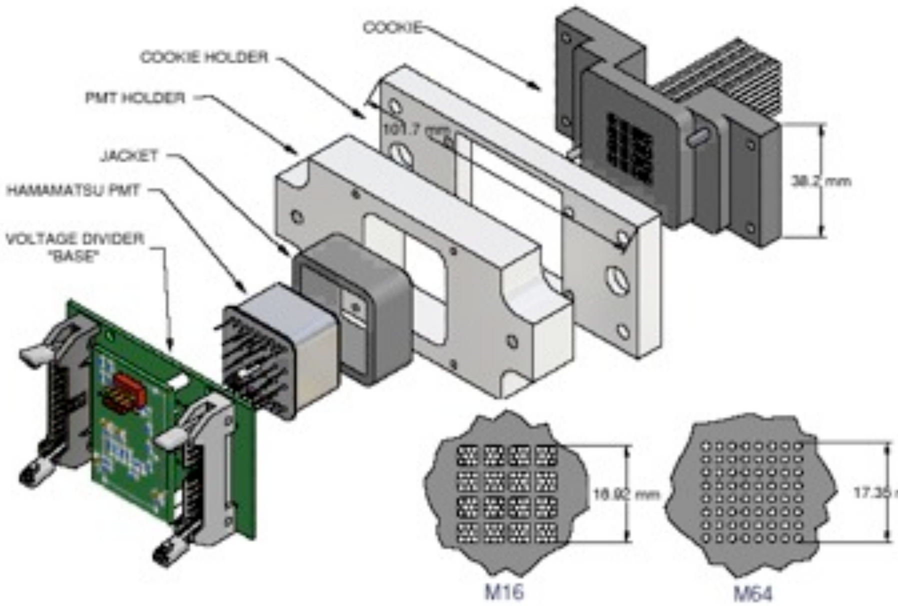
The MINOS Detectors

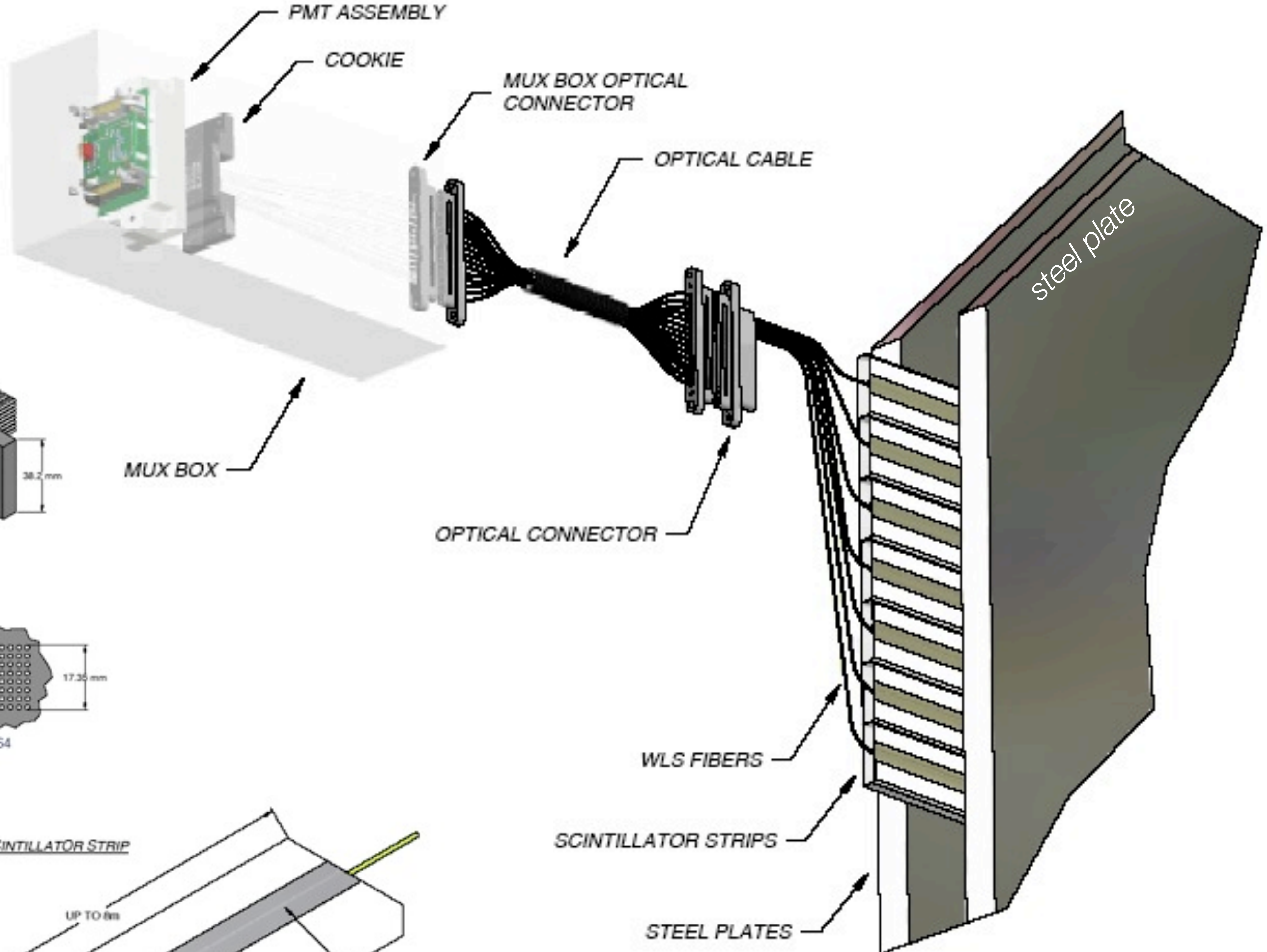
MINOS uses two functionally equivalent detectors:

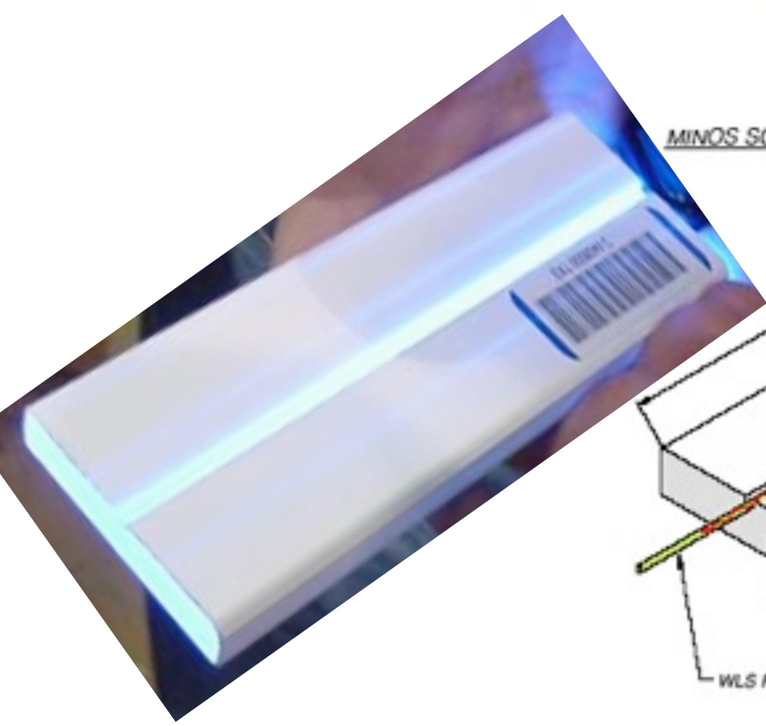
- 2.54 thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips
- optical fiber readout to multi-anode PMT's

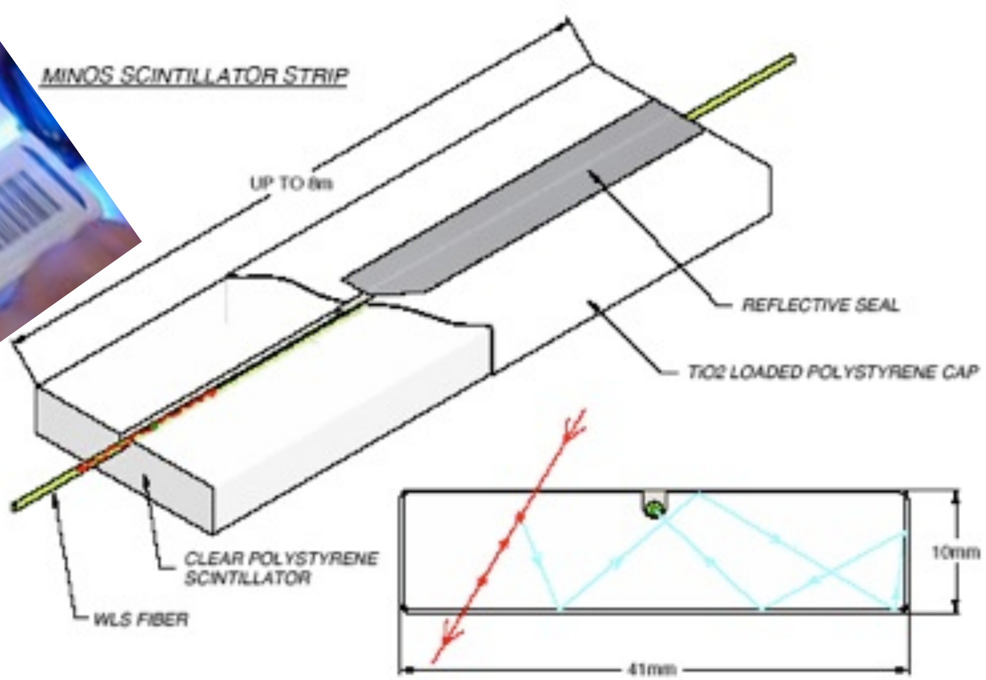










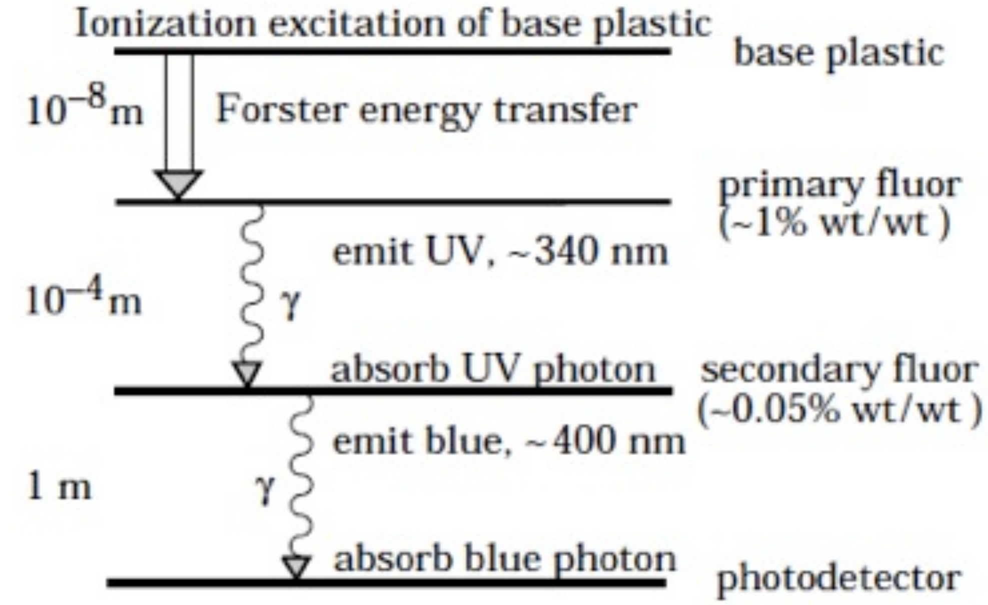


MINOS Detector

scintillator modules layered on steel plane

“strong back”. Removed after plane is hung in place

Scintillation process



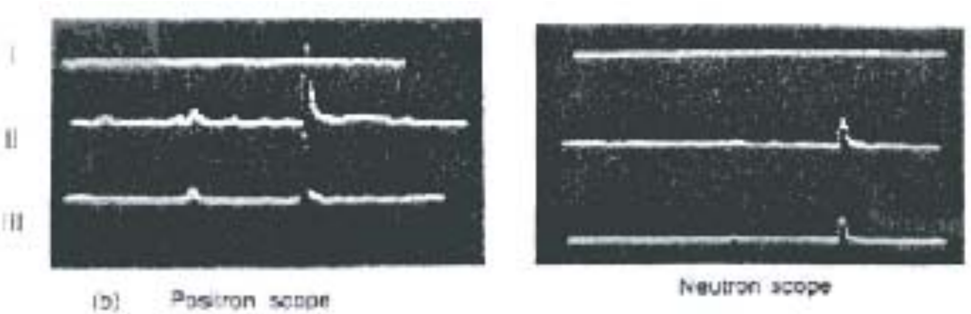
- Scintillators are solid or liquid materials that produce light shortly after absorbing energy from a passing particle
- "Shortly" here is characterized by the decay time of the scintillator with the number of photons emitted varying as $n(t) = k(1 - e^{-t/\tau})$. The scintillators with lowest dead times have tau's at low as 5 ns. Typical values are 10-100 ns.
- The number of scintillation photons produced per unit energy deposited goes as:

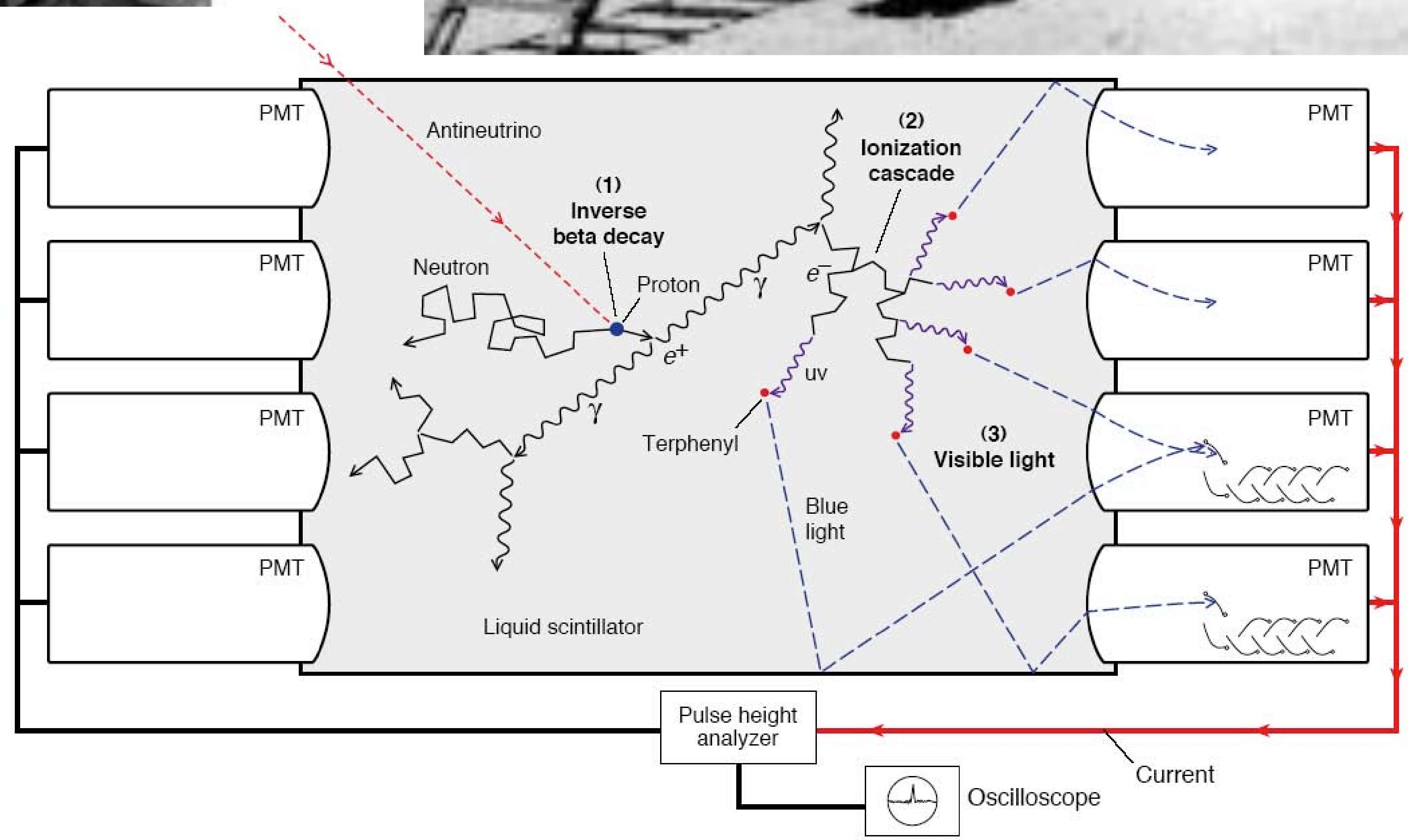
$$n = n_0 \frac{dE/dx}{1 + BdE/dx}$$

  where B is "Birk's" constant and accounts for saturation of the scintillator at high energy depositions.

- Scintillation light is emitted in a distribution peaked typically around 350-400 nm. It is common to use compounds (eg. PPO, POPOP) which absorb this light and re-emit it at longer wavelengths where the scintillator has less absorption and where the fiber absorbs strongly.
- Light is captured by the fiber at typically 420 nm and reemitted at around 470 nm and is carried to the ends by total internal reflection. Transport characterized by a short attenuation length (~2 m) and a long attenuation length (~8 m).
- Final photon spectrum is well matched to wavelength response of PMT's

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

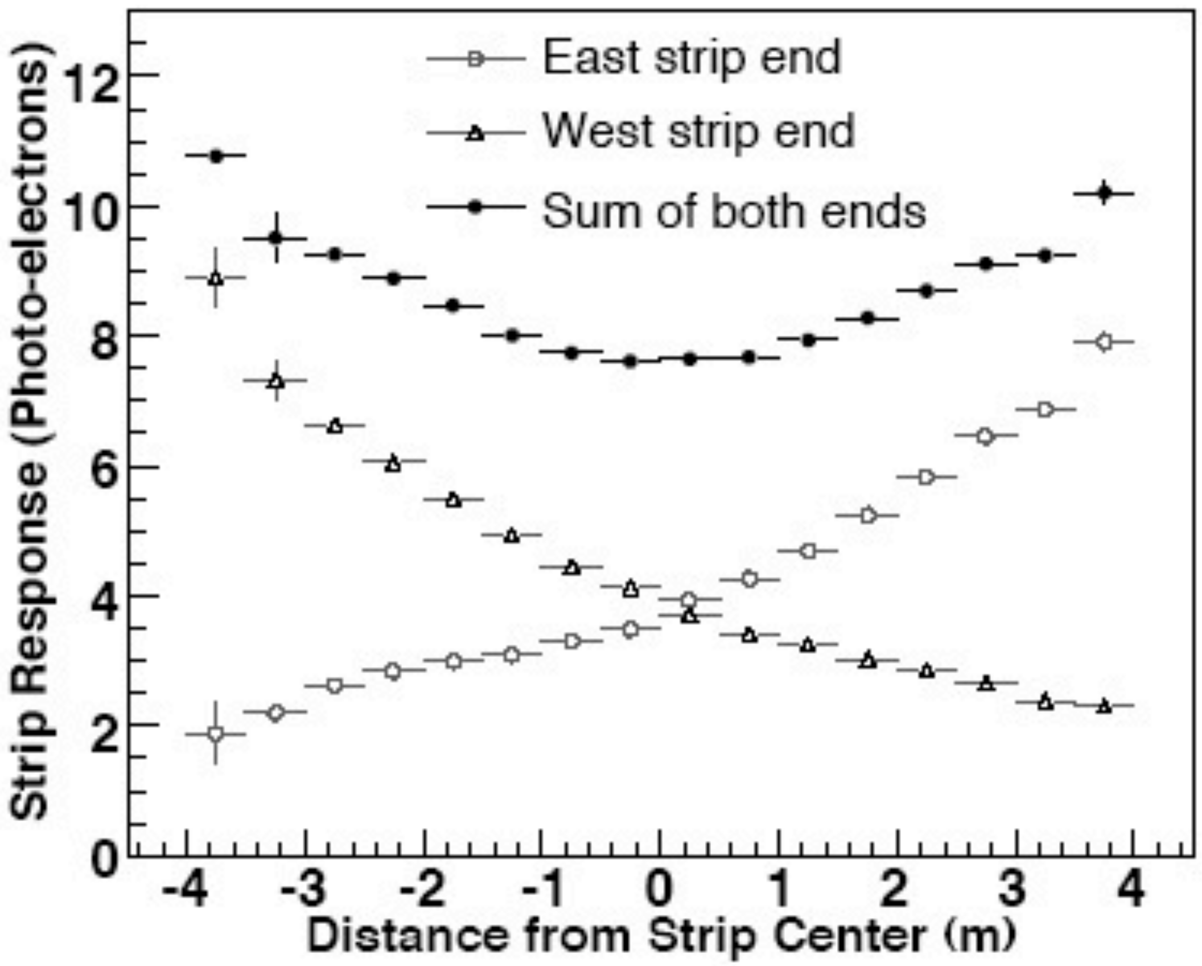




Los Alamos Science, Number 25 1997

Project Poltergeist, 1953

MINOS scintillator system



Single strip muon hit efficiency

Single sided:

ε=1-exp(-2) = 86%

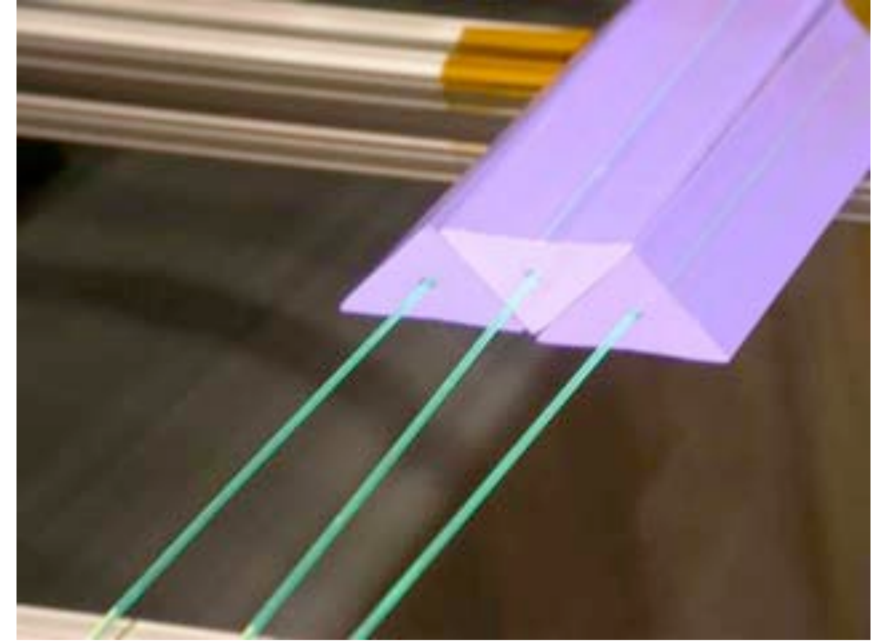
Double sided:

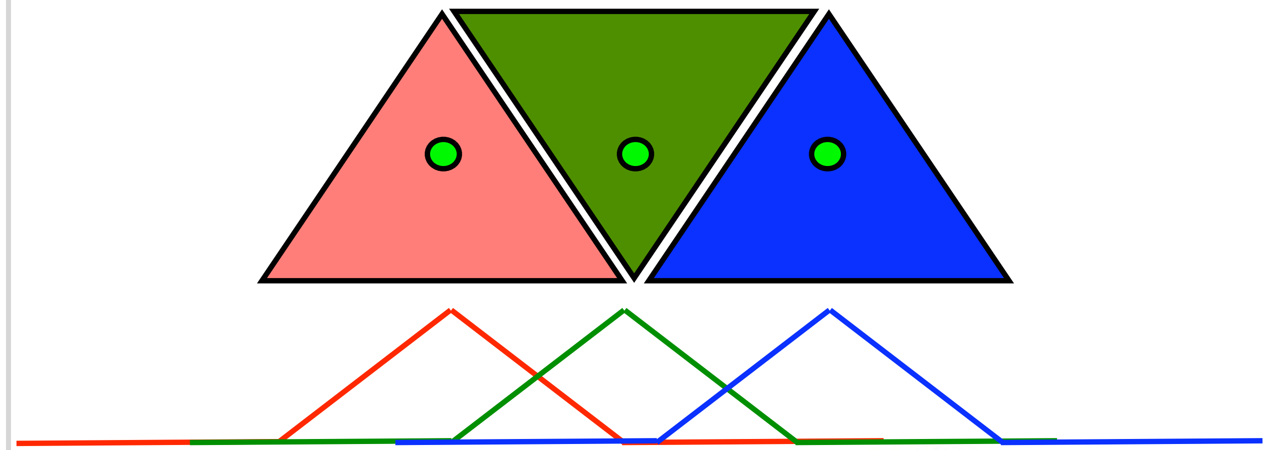
ε=1-exp(-8) = 99.97%

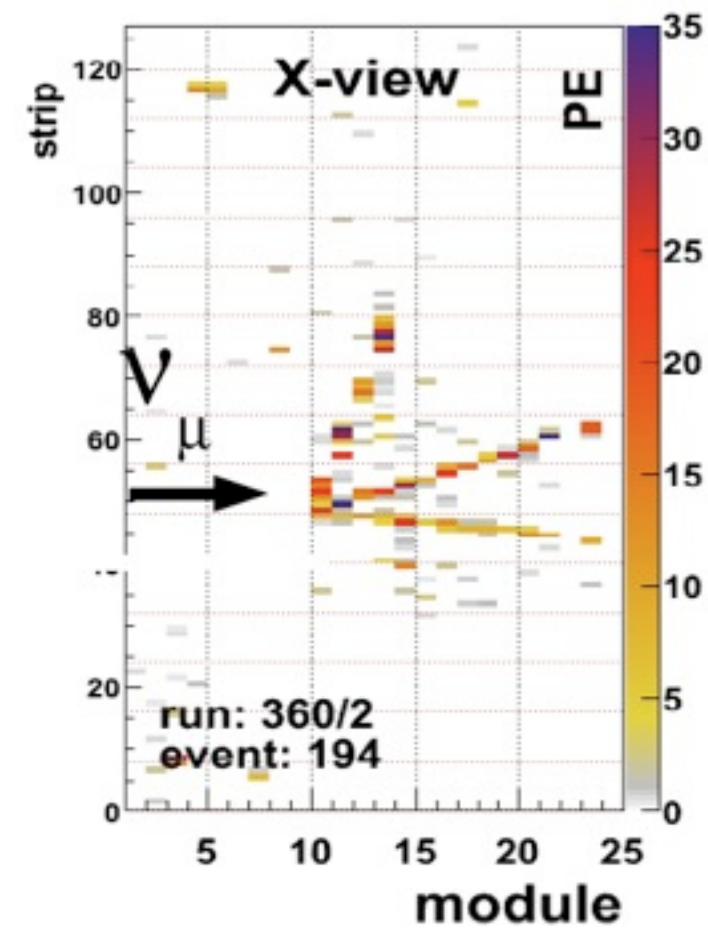
Fig. 26. Average light output from in-situ Far Detector strips as a function of distance from their center for normally incident MIPs. The data shown are from stopping cosmic-ray muons, for which containment criteria cause lower statistical precision at the ends of the strips.

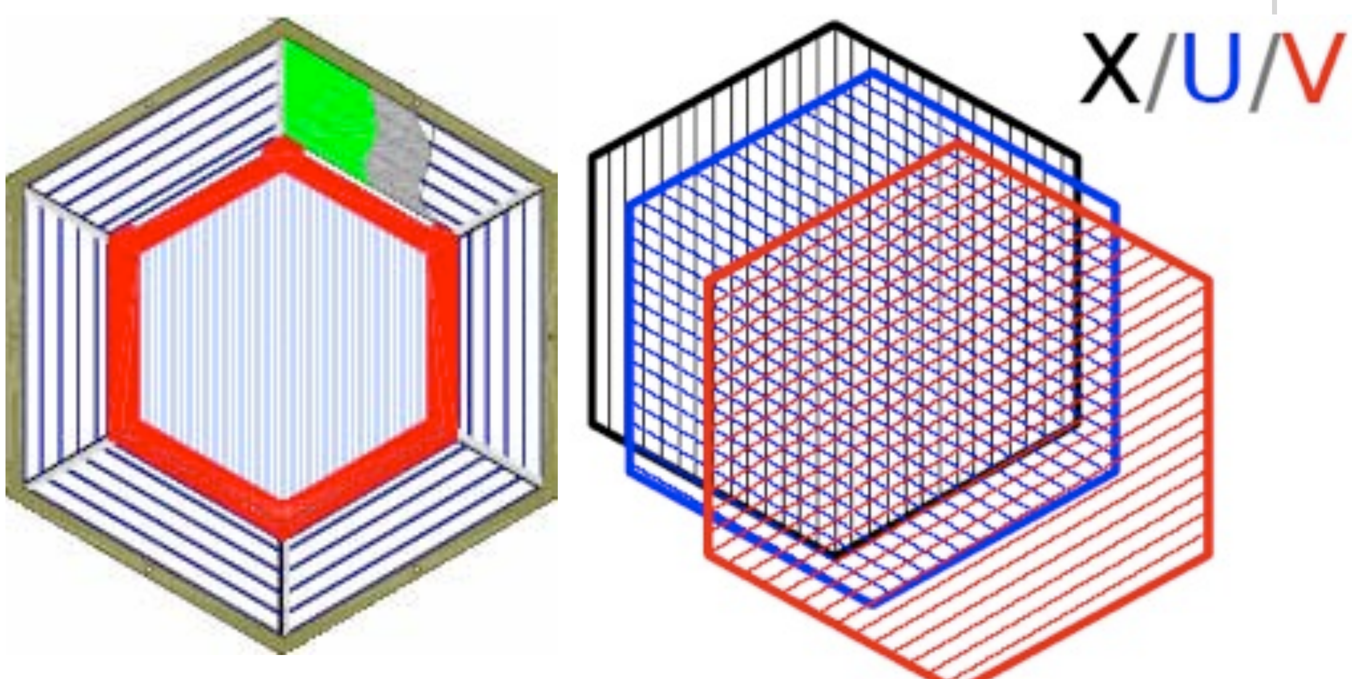
MINERvA

- MINERvA incorporates several improvements in tracking resolution
- Triangularly extruded scintillator bars allows track position to be estimated by light-sharing fractions
- Three tracking views. Resolves ambiguity when track travels along one of the strip directions or overlaps with another track in one view



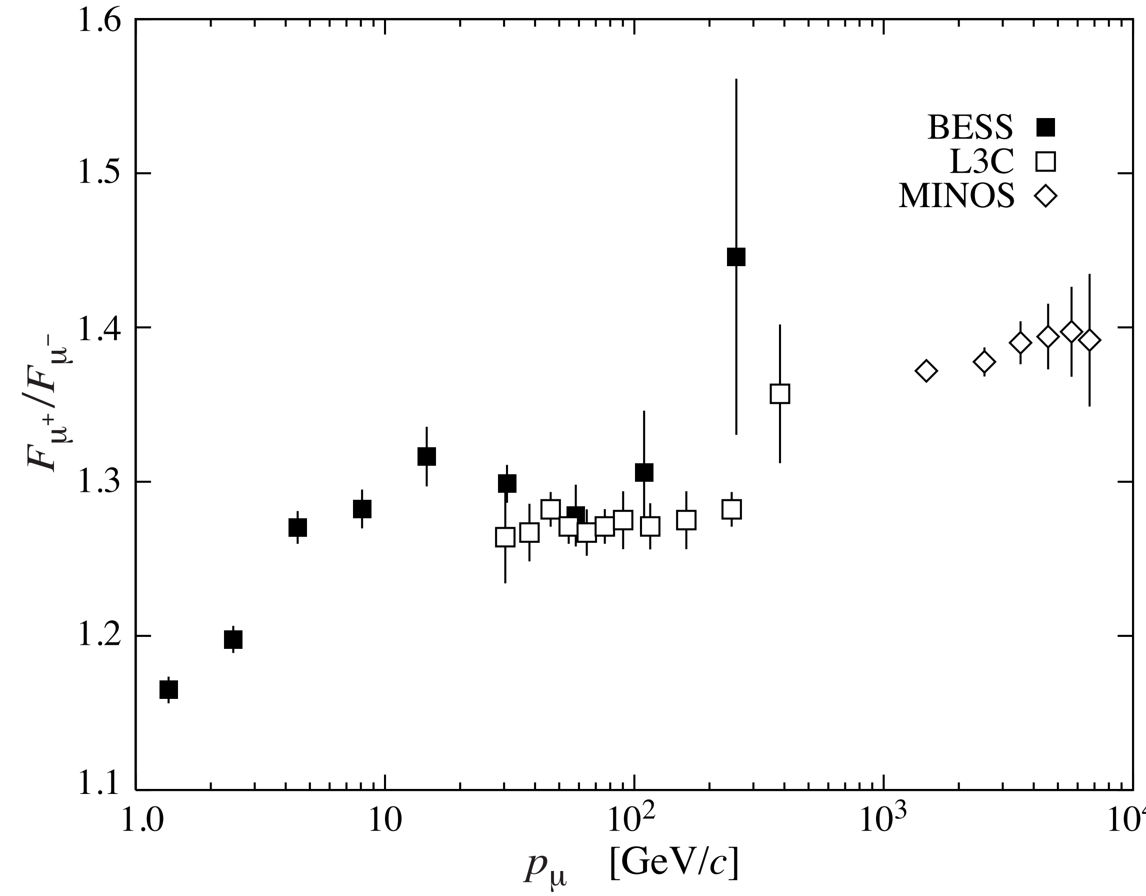






Why magnetize?

- *Containment:* A magnetic field can keep muons from exiting the sides of your detector
- *Momentum measurement:* If the muon does exit your detector, the curvature of the track tells you the momentum even when you couldn't otherwise get it from the range of the particle
- *Charge sign:* There are physics measurements in knowing the charge sign of the muons in your detector. Crucial for the "golden channel" at a neutrino factory:



Cosmic-ray μ+/μ- ratio

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \quad \begin{cases} \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \\ \nu_e \rightarrow \nu_\mu \end{cases}$$

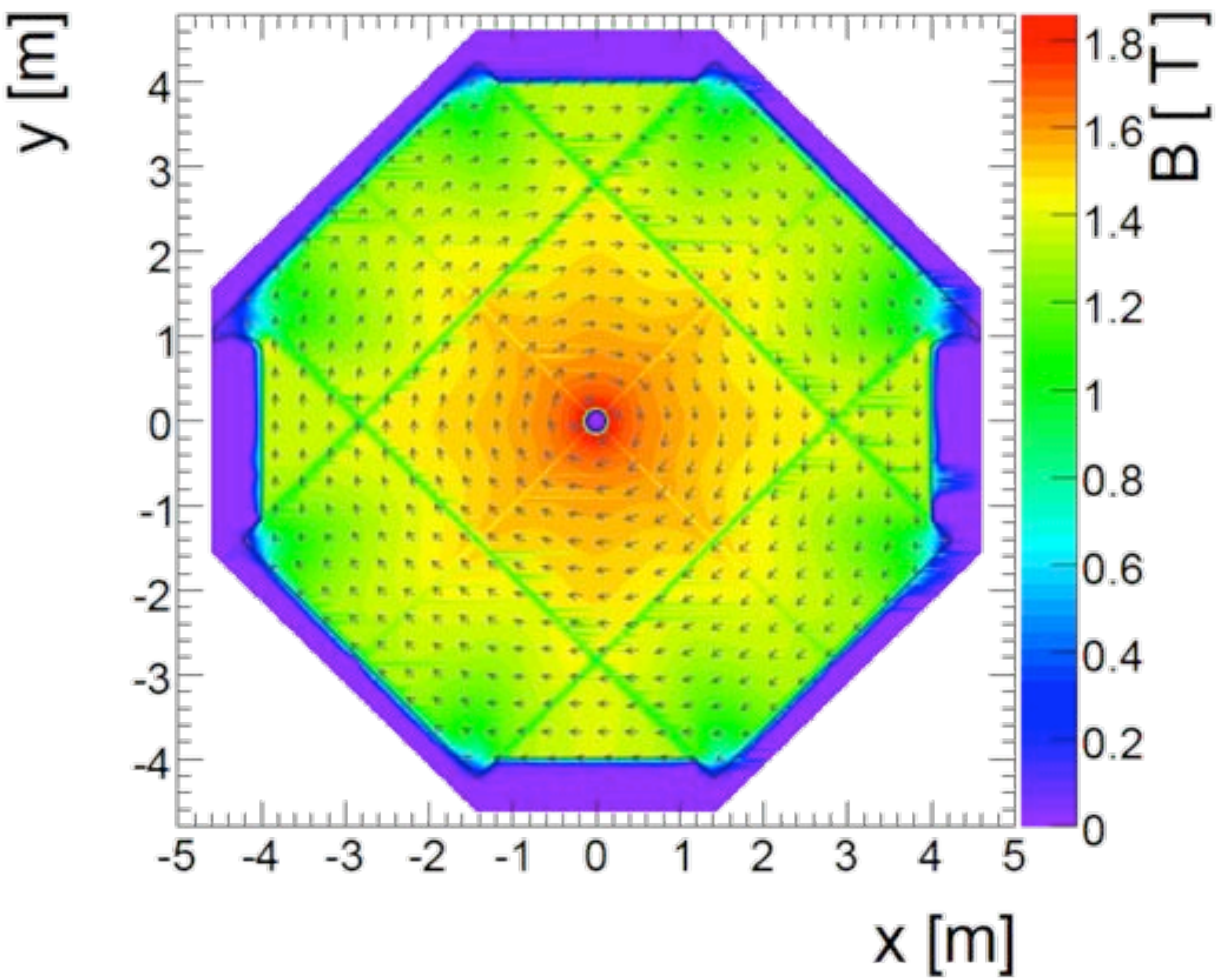
$$\bar{\nu}_\mu + A \rightarrow \mu^+ + X$$

$$\nu_\mu + A \rightarrow \mu^- + X$$

production → *oscillation* → *detection*

"wrong" sign!

Magnetic field in MINOS



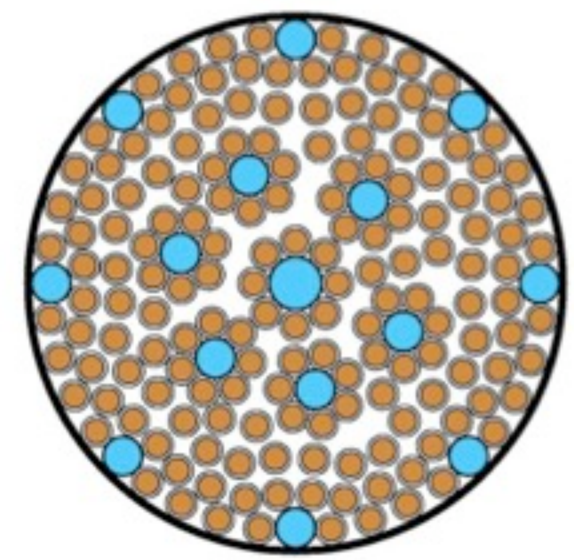
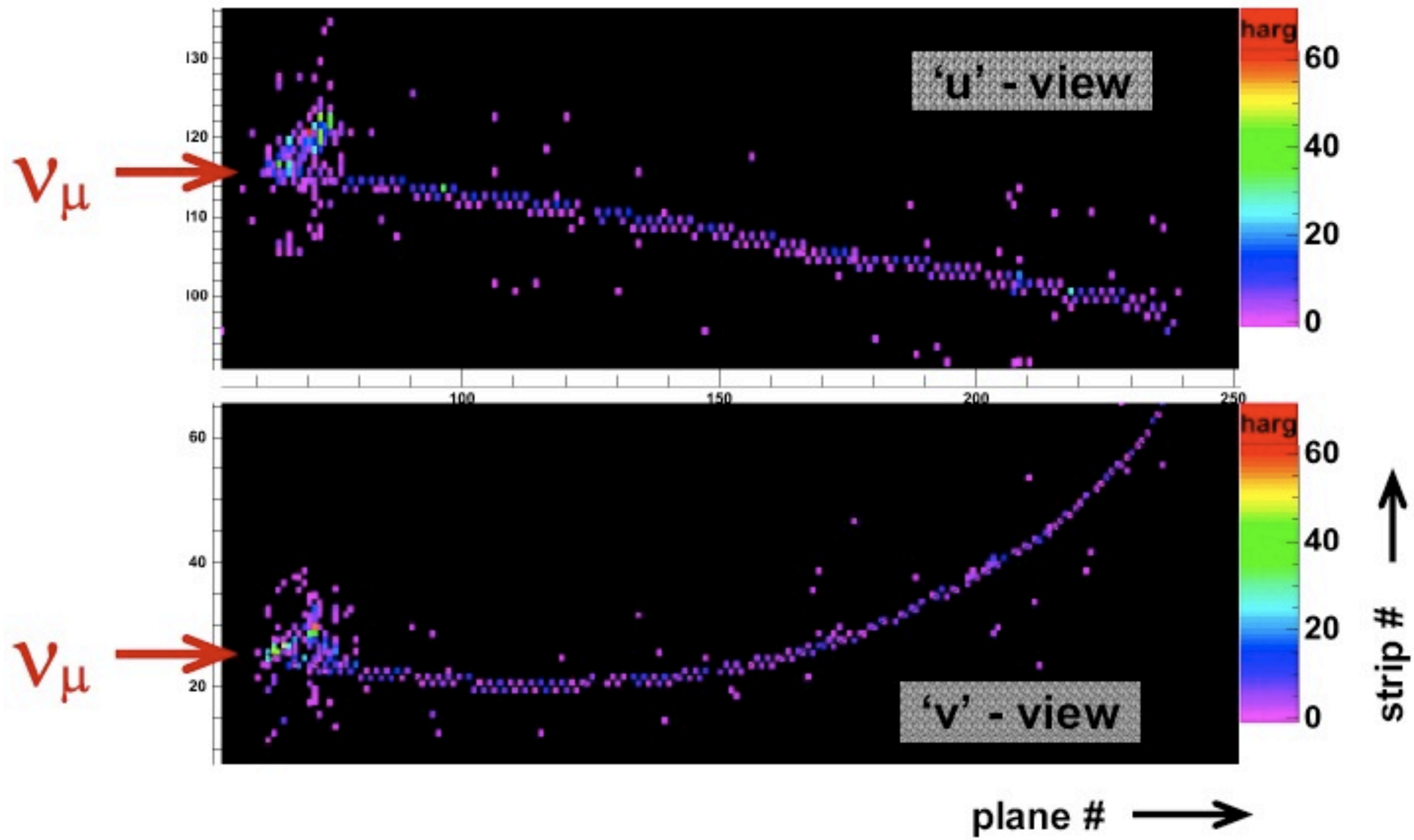


Fig. 6. Sketch of a cross section of one of the far detector supermodule coils. The larger diameter circles represent the copper cooling tubes and the smaller circles are the 190 turns of 1/0 gauge stranded copper wire. The outlines of these conductors are to-scale representations of the insulator thickness. The outer circumference of the assembly is a copper-sheet jacket that is directly cooled by eight cooling tubes.

- 15.2 kA-turn total current
- 80 A supply
- 10 gauge copper wire, water cooled

MINOS Event



‘u’ - view
‘v’ - view
harg
60
40
20
0
130
120
110
100
100
150
200
250
60
40
20
strip #
plane #

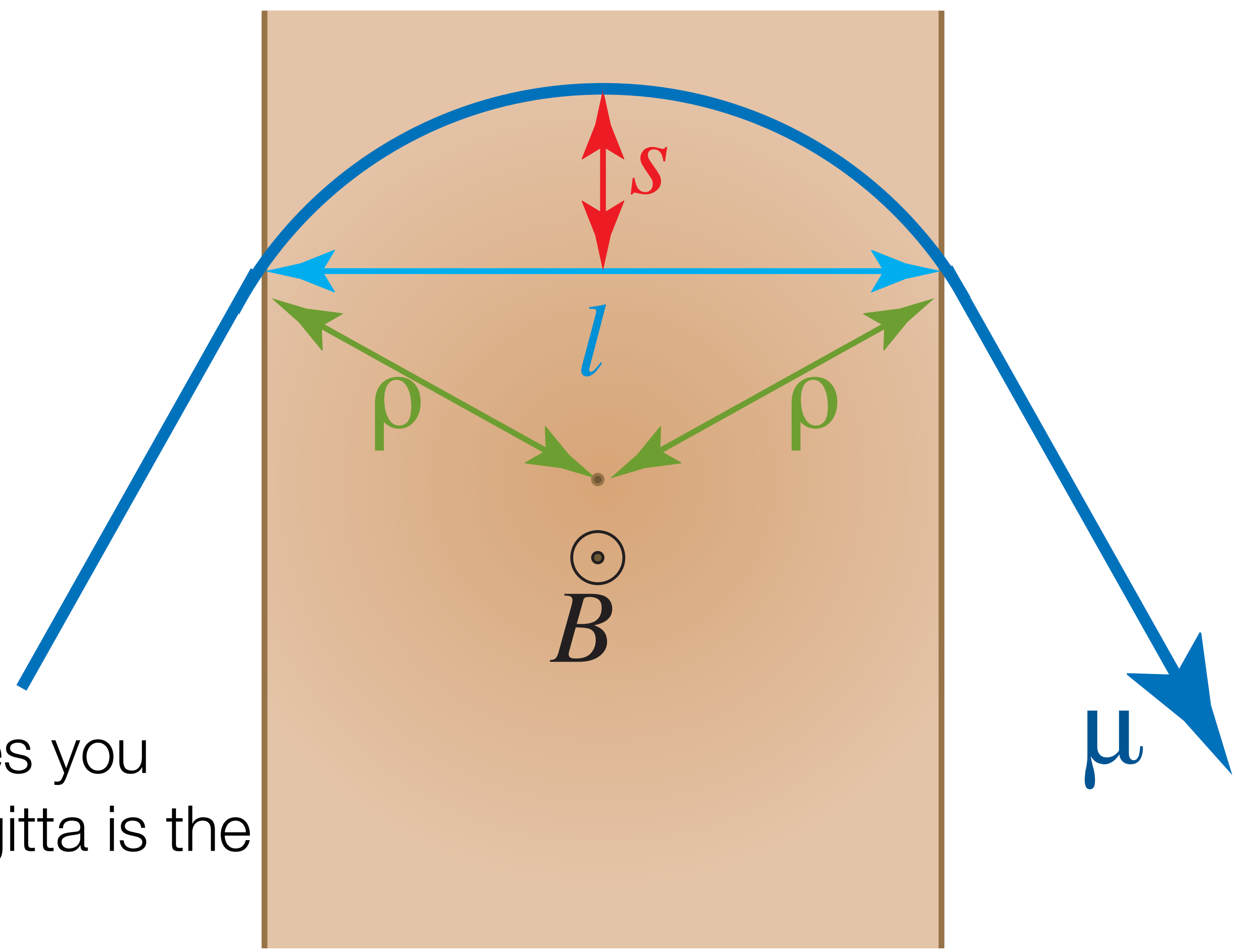
Track momentum using curvature

A particle with momentum p, traveling through a constant transverse magnetic field B will travel on a circle of radius ϱ

$$p[\mathrm{GeV}/c] = 0.2998 B[\mathrm{T}]\rho[\mathrm{m}]$$

$$\rho = \frac{l^2}{8s} + \frac{s}{2}$$

$$p \simeq 0.3\frac{Bl^2}{8s}$$



Measurement of sagitta and chord gives you momentum. Detector resolution on sagitta is the same as the momentum resolution:

$$\left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

More common to talk about the track curvature

$$k = \frac{1}{\rho}$$

which has roughly Gaussian errors.

Curvature errors for multiple position samples

- The uncertainty in curvature for a track which travels a distance *L* in a magnetic field *B* whose position is sampled *N* times at uniform intervals with a position uncertainty ε has been worked out by Gluckstern [NIM 24 (1963) 381-389]:

$$\sigma^2_{k,R} = \frac{\epsilon^2}{L^4}\frac{720}{N+5}$$

Notice relative importance of L and ε

- Gluckstern has also worked out the contribution to the uncertainty in the curvature from multiple-scattering:

$$\sigma^2_{k,M.S.} = \frac{KC_N}{L}$$

- *K* is the RMS projected multiple scattering angle per unit thickness *x*

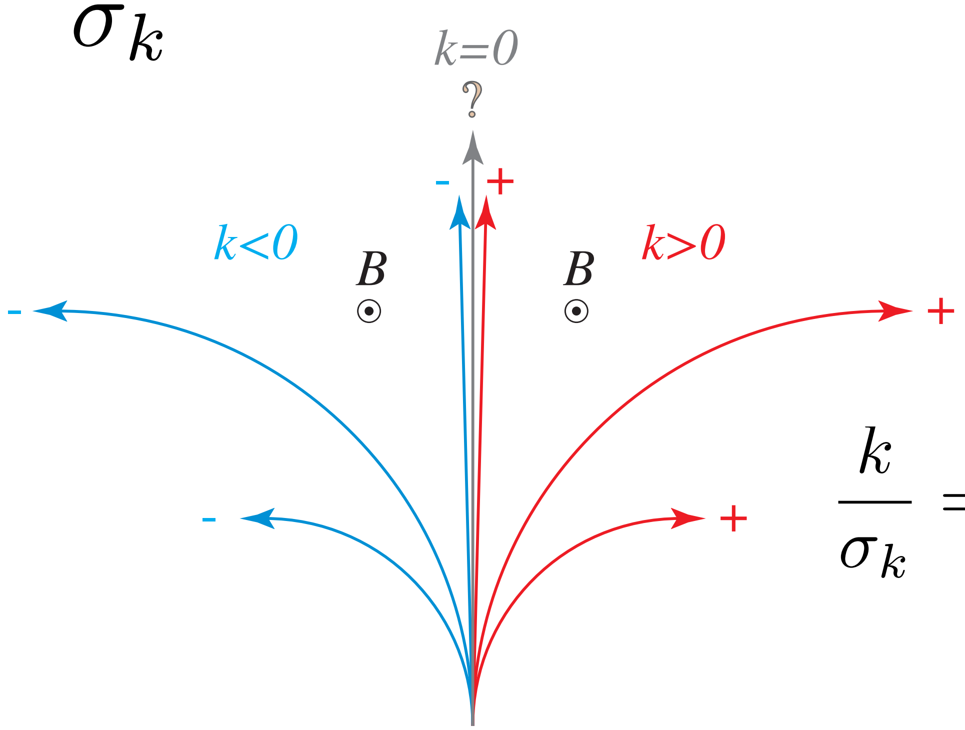
$$K = \frac{\theta_0}{\sqrt{3}x} = \frac{13.6\ \mathrm{MeV}}{\beta cp} z\sqrt{\frac{1}{3xX_0}}\left[1 + 0.038\ln(x/X_0)\right]$$

- C_N is a constant from lookup table. C_N=1.43 for large N.

- *x* is the distance traveled in the medium
- *z* is the charge of the particle

How well do we measure track curvature?

$\frac{k}{\sigma_k}$ determines how well the track curvature, and hence sign is known



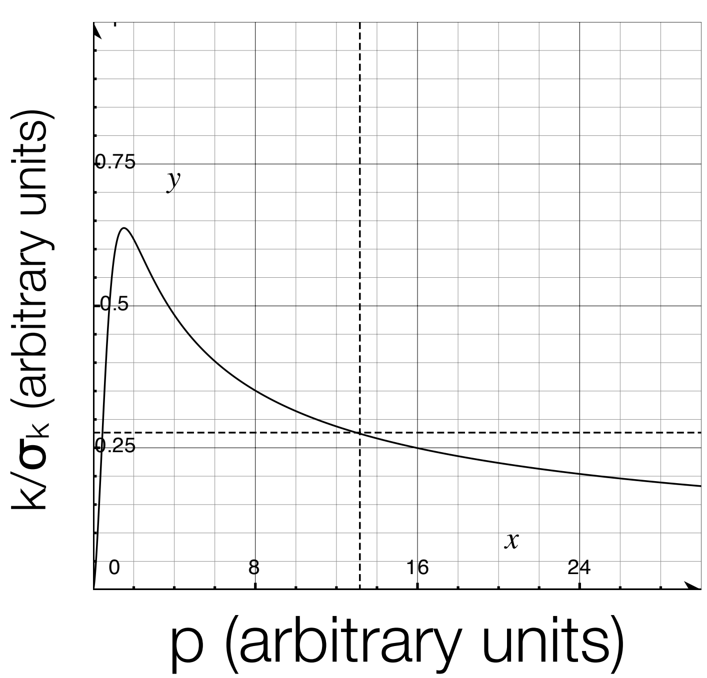
$$\frac{k}{\sigma_k} \quad k \leftarrow k = \frac{0.3B}{p} \qquad \sigma_k \leftarrow \sigma_k^2 = \sigma_{k,R}^2 + \sigma_{k,M.S.}^2$$

$$\frac{k}{\sigma_k} = \frac{0.3B}{\left(\frac{720\epsilon^2 p^2}{L^4(N+5)} + 0.0079 C_N \sqrt{\frac{p^2+m^2}{x X_0}}\left(1 + 0.038 \log \frac{x}{X_0}\right)\right)^{\frac{1}{2}}}$$

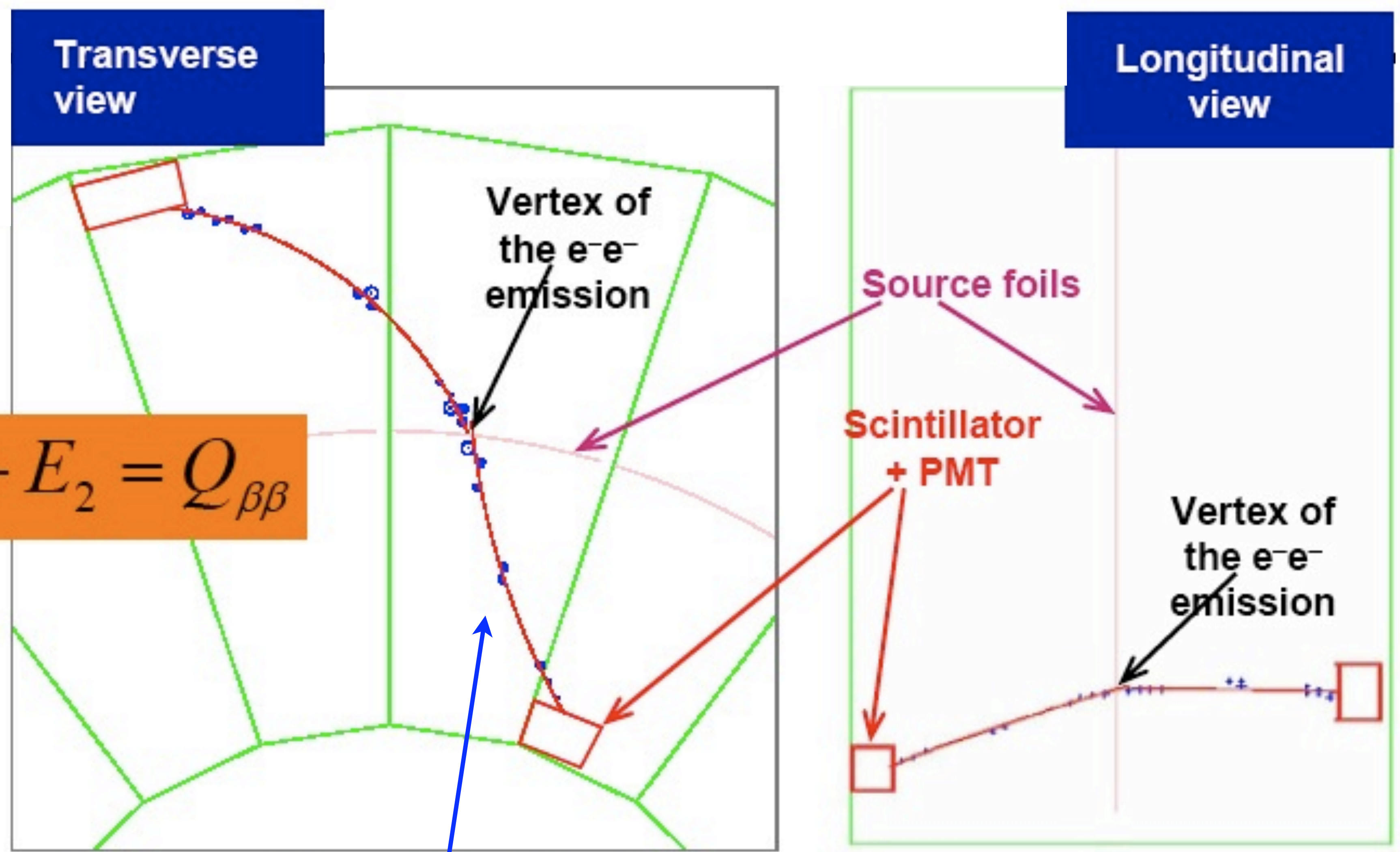
units: [T], [GeV], [m]

$$\text{Remember}: \; L \propto p, \; N \propto p, \; \text{and} \; x \propto p$$

- High field
- Small **ε**
- Large L (low Z to keep dE/dx low and range high)
- Large X_0 (low Z)
- “Just” right momentum (see plot at left)
- MINOS: 10% momentum resolution using curvature



Tracking in the NEMO-3 detector (2νββ)



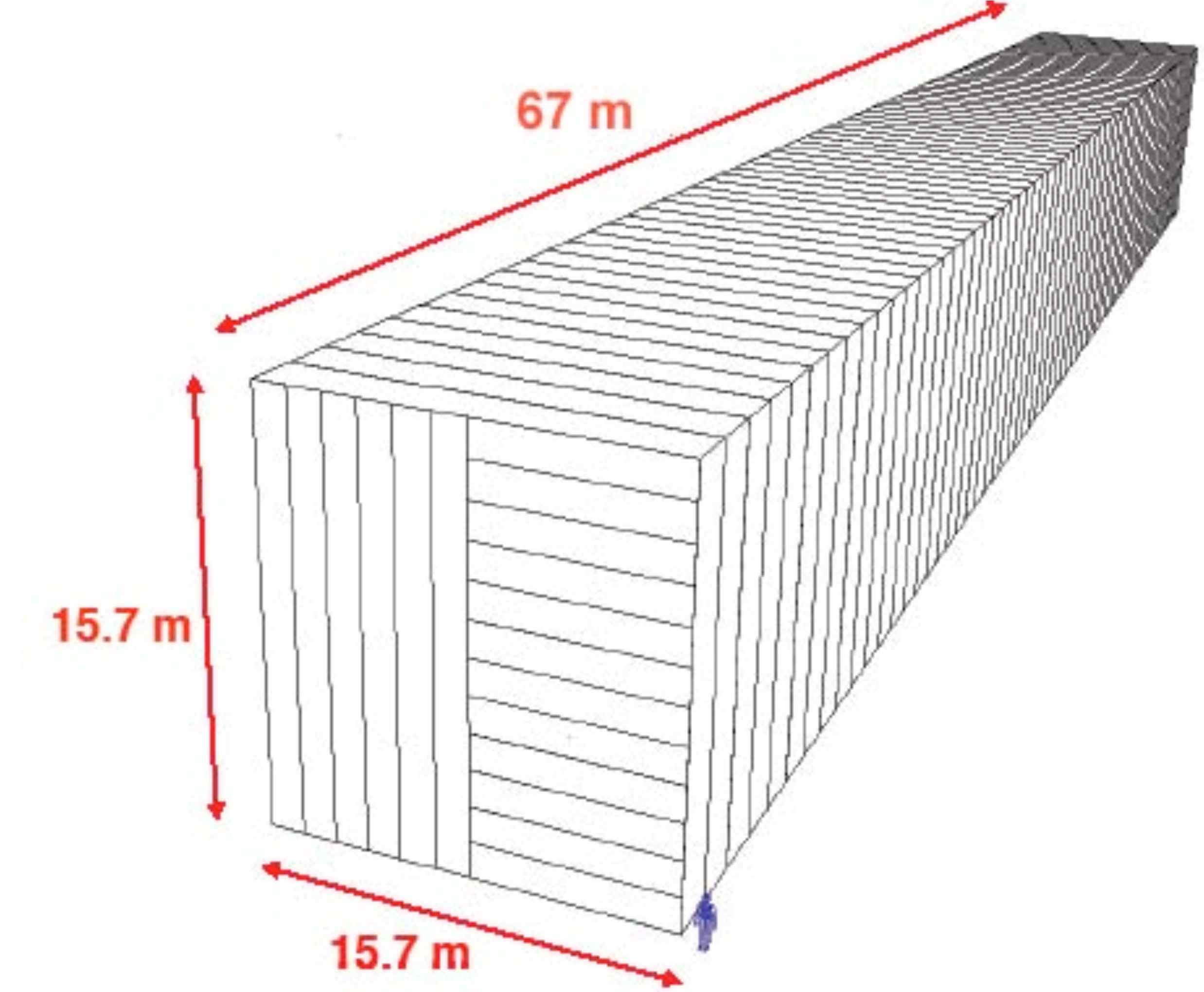
$$E_1 + E_2 = Q_{\beta\beta}$$

Wire chamber planes

Low density medium and excellent sagitta measurement yields about a 4% measurement for electrons at 4 MeV

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 $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ 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



<u>*Liquid scintillator*</u>

(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

<u>*Extruded PVC*</u>

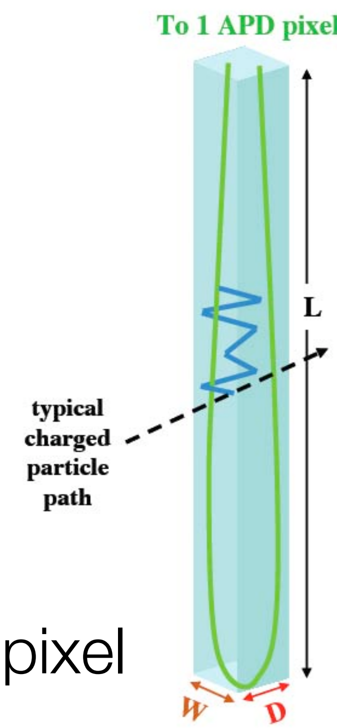
(5.4 ktons)

15% anatase TiO_2 for high reflectivity

<u>*Wavelength shifting fiber*</u>

(18k km)

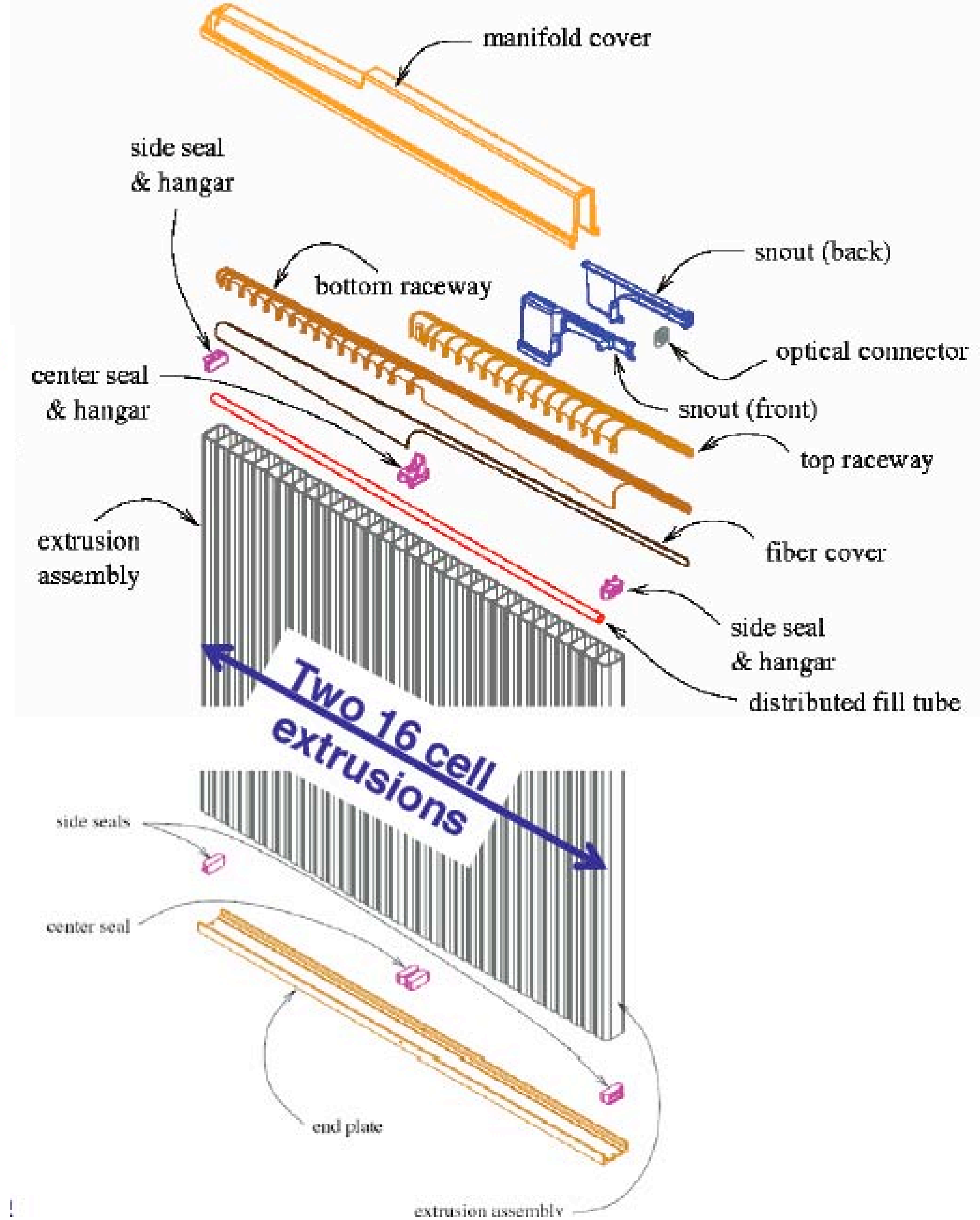
- 0.7 mm diameter
- Looped, both ends to same readout pixel



<u>*Avalanche photodiodes (APD)*</u>

(14k boards, 32 channels each)

- 85% quantum efficiency at long wavelengths
- Collect 30 photoelectrons per muon crossing at far end of cell

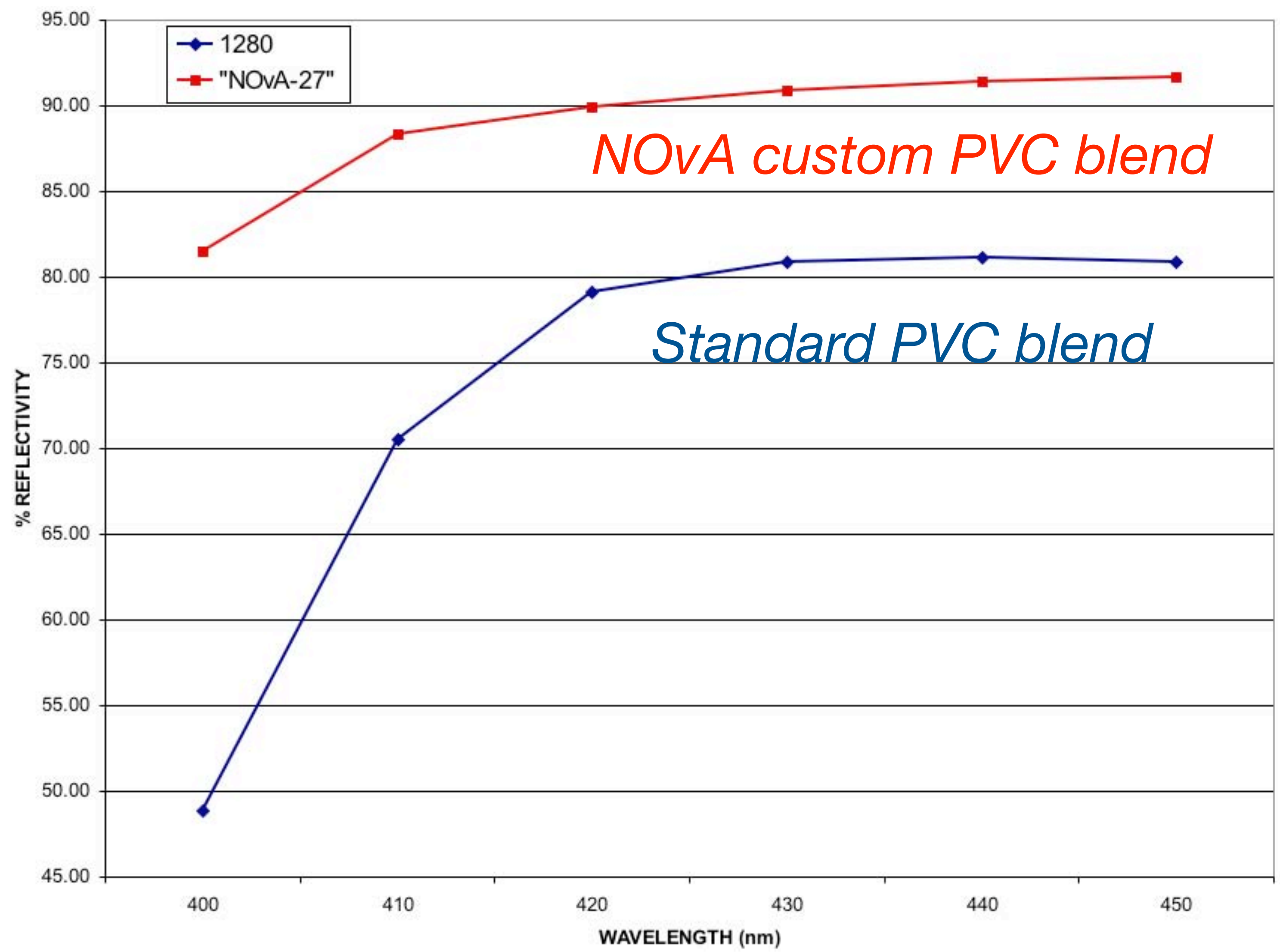


Detector design

Wall reflectivity

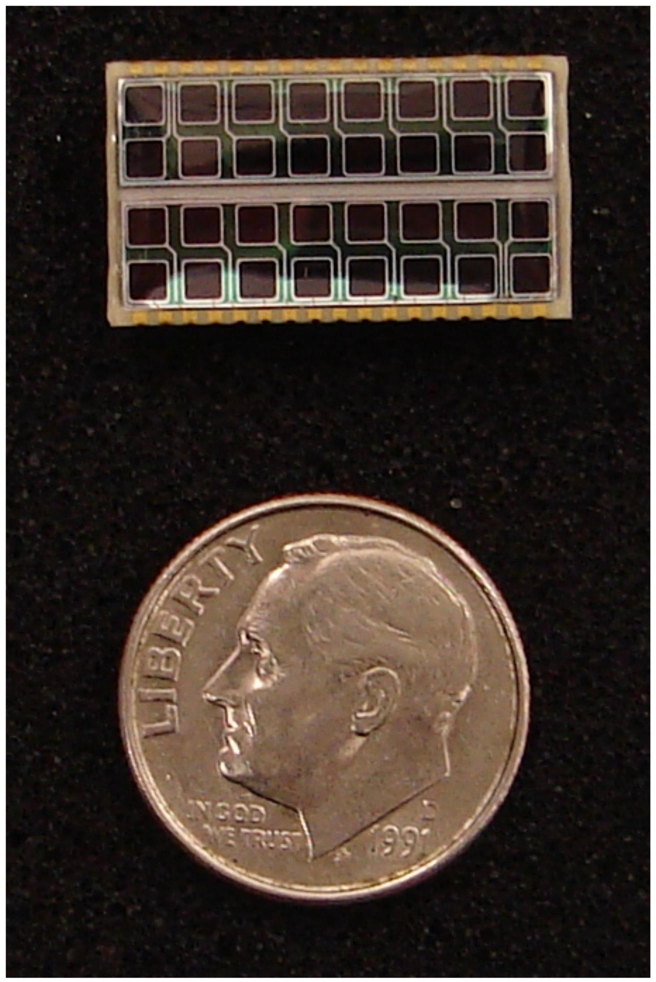
- In NOvA cell, a photon typically bounces off the cell walls 10 times before being captured by a fiber
- This makes the reflectivity of the cell wall of crucial importance to maximizing light output:
  - $0.8^{10} = 0.11$
  - $0.9^{10} = 0.35$

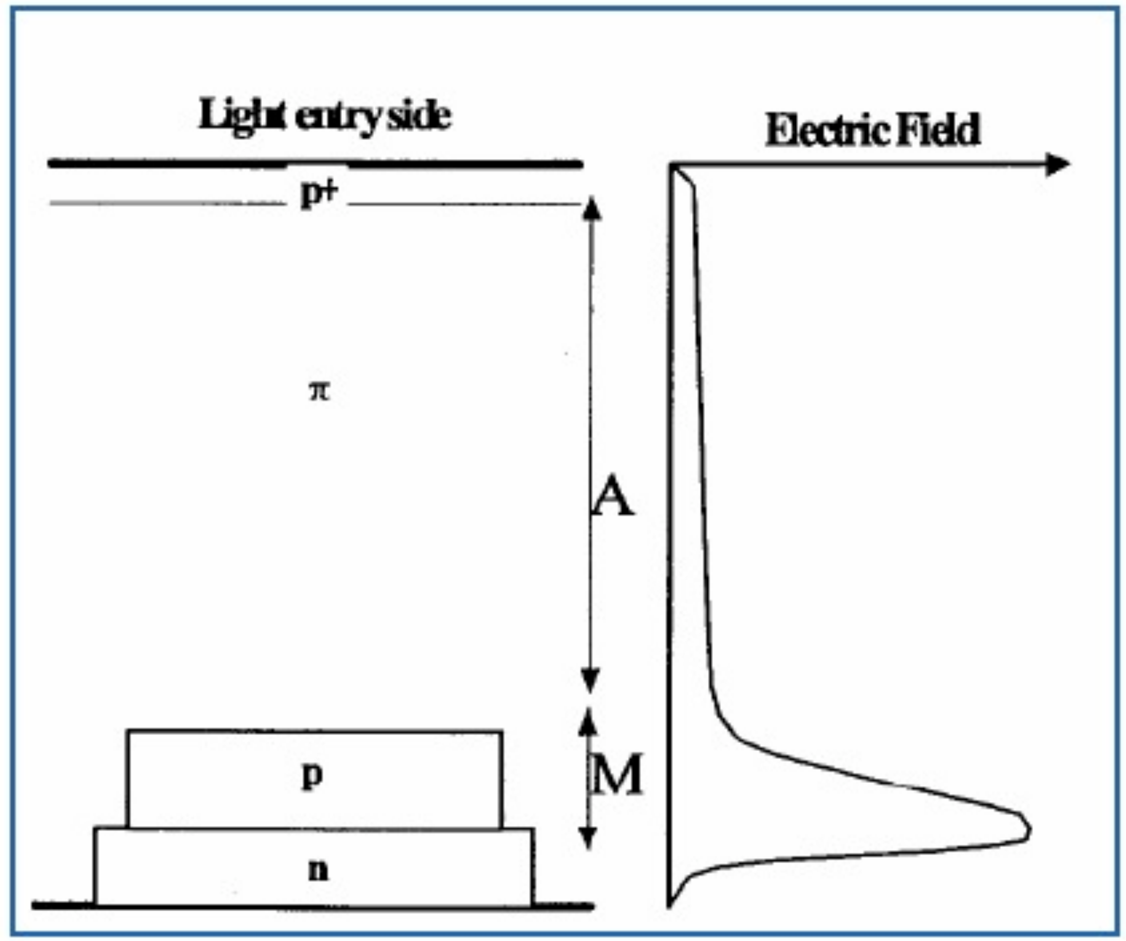
10% improvement in reflectivity yields factor 3 more light!



Wall reflectivity is issue for other scintillator detectors which co-extrude scintillator with a TiO2 reflective coating

Avalanche photo diodes (APD)





Absorption region

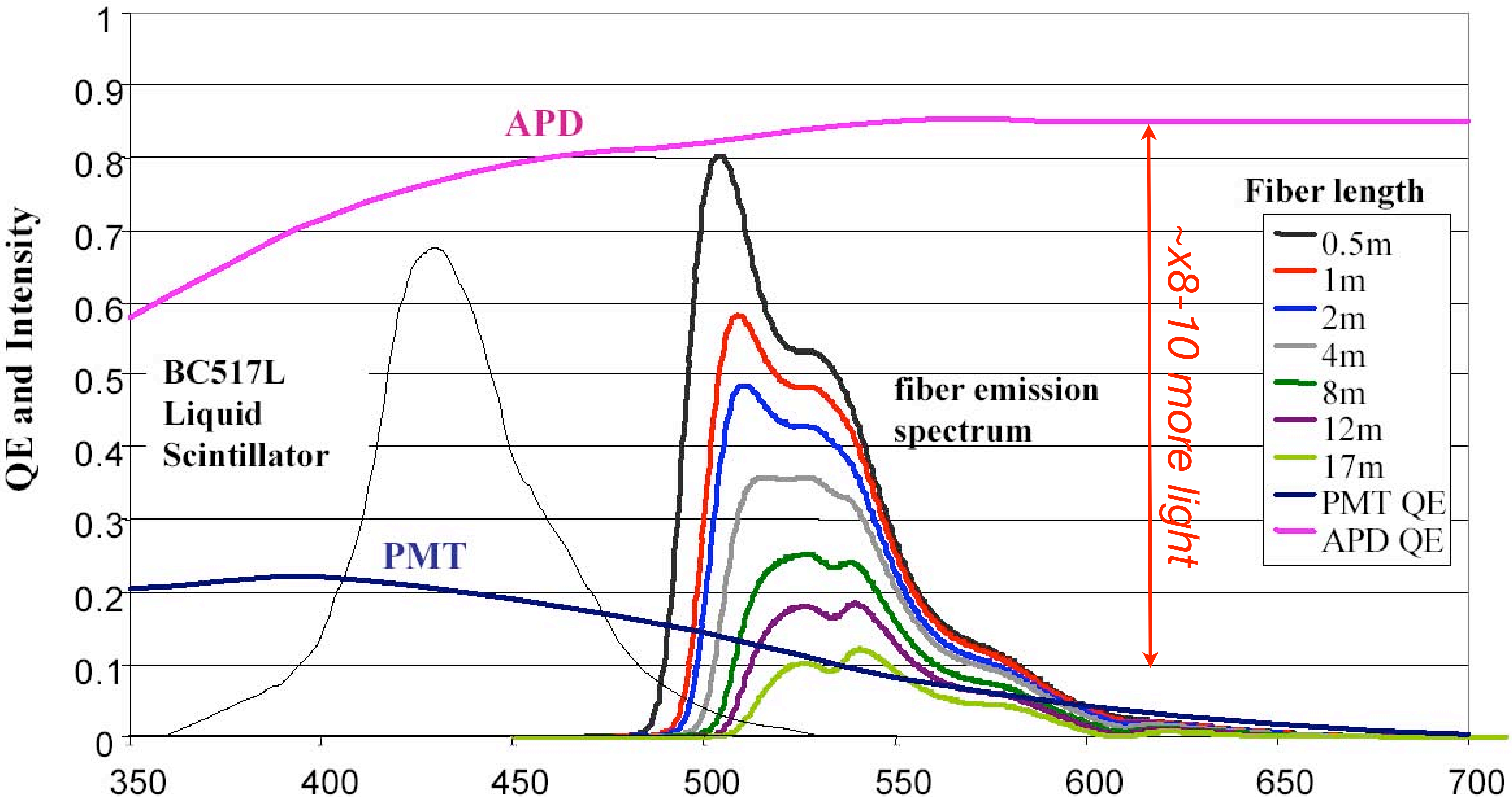
Multiplication region

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

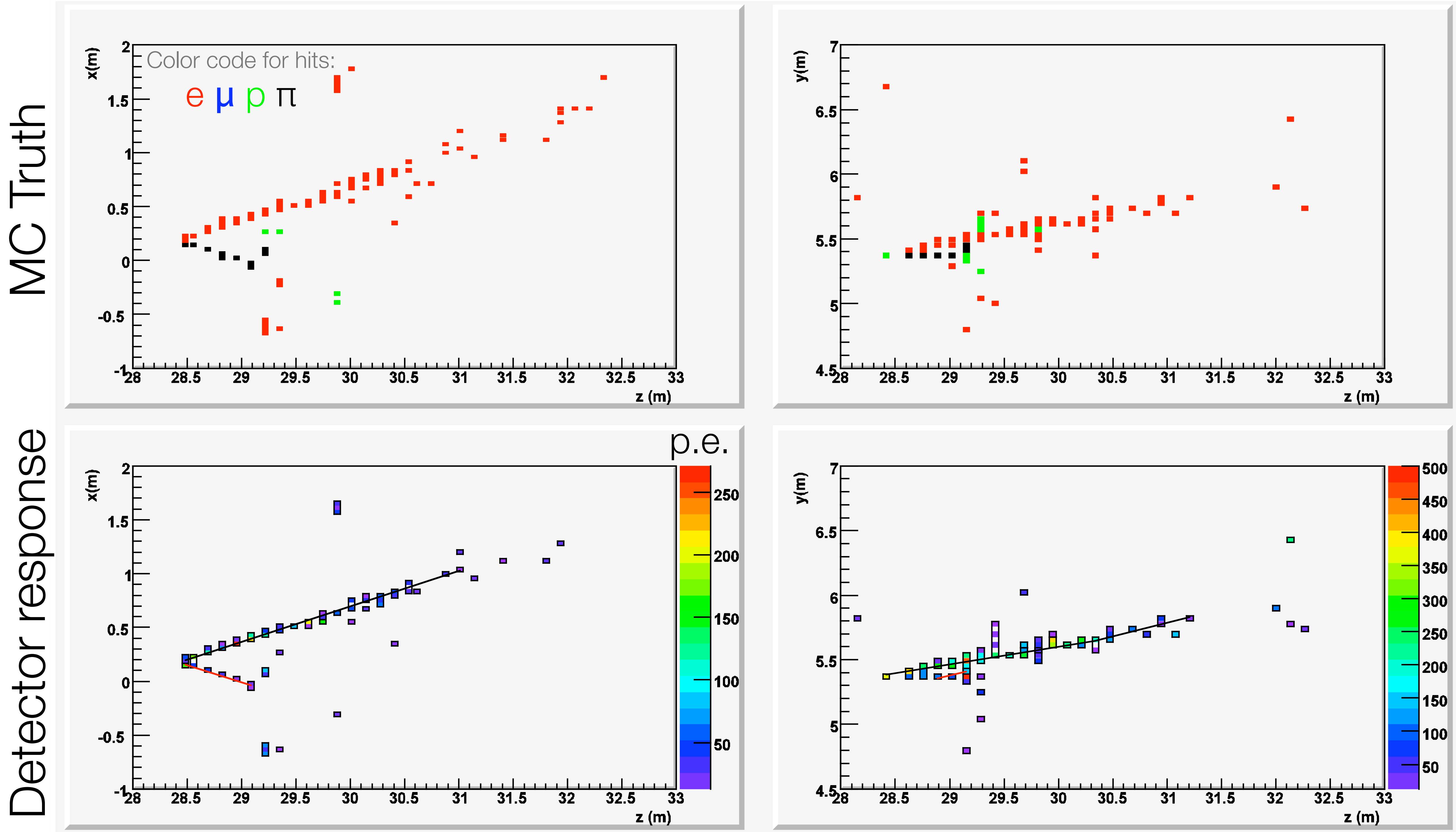
NOvA Fiber and Photodetector



scintillation light ⟶ re-emission by fiber

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

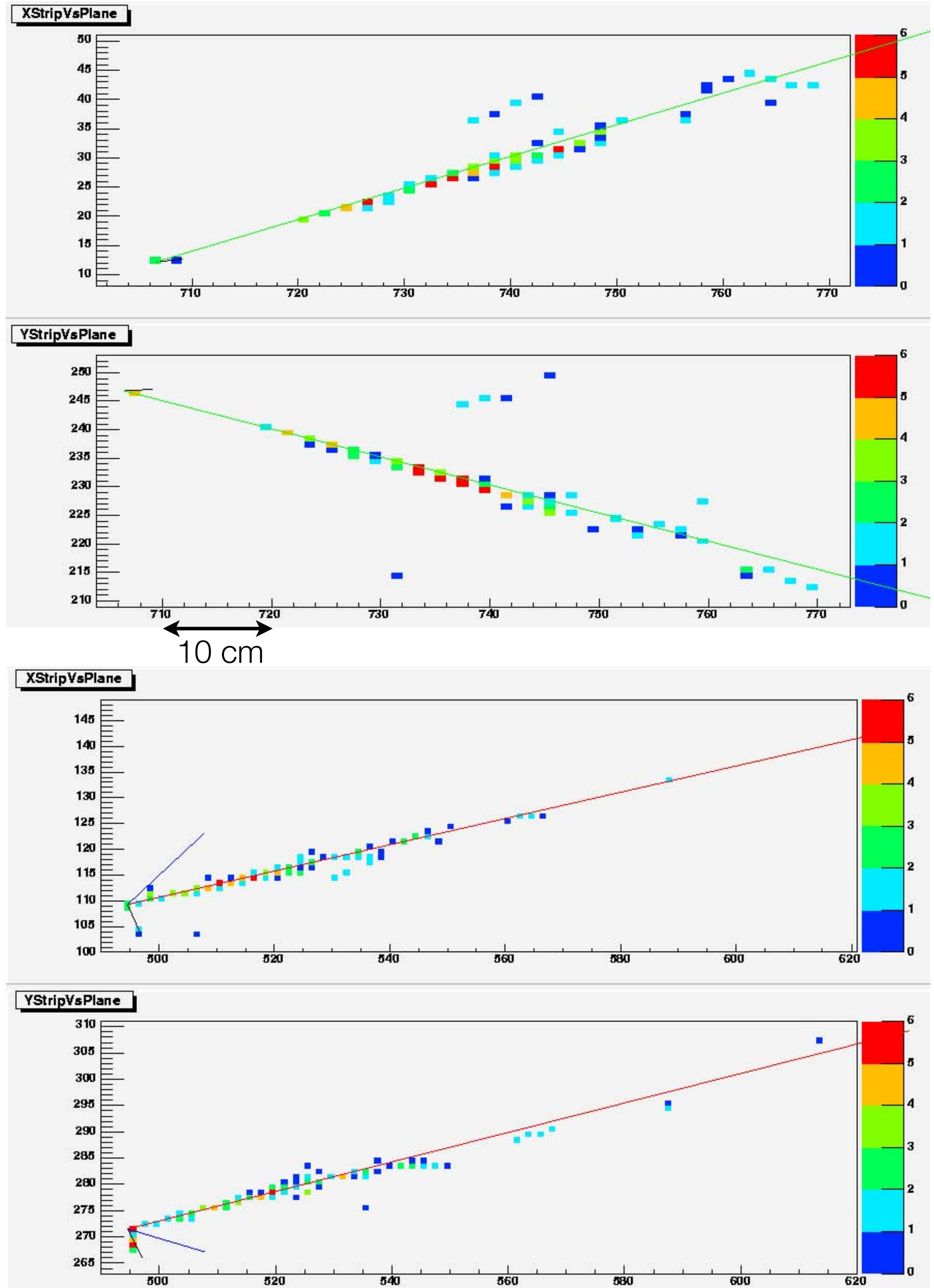
ν_e (2.4 GeV) + N$\rightarrow$ e^- (1.8 GeV) + X (Res)



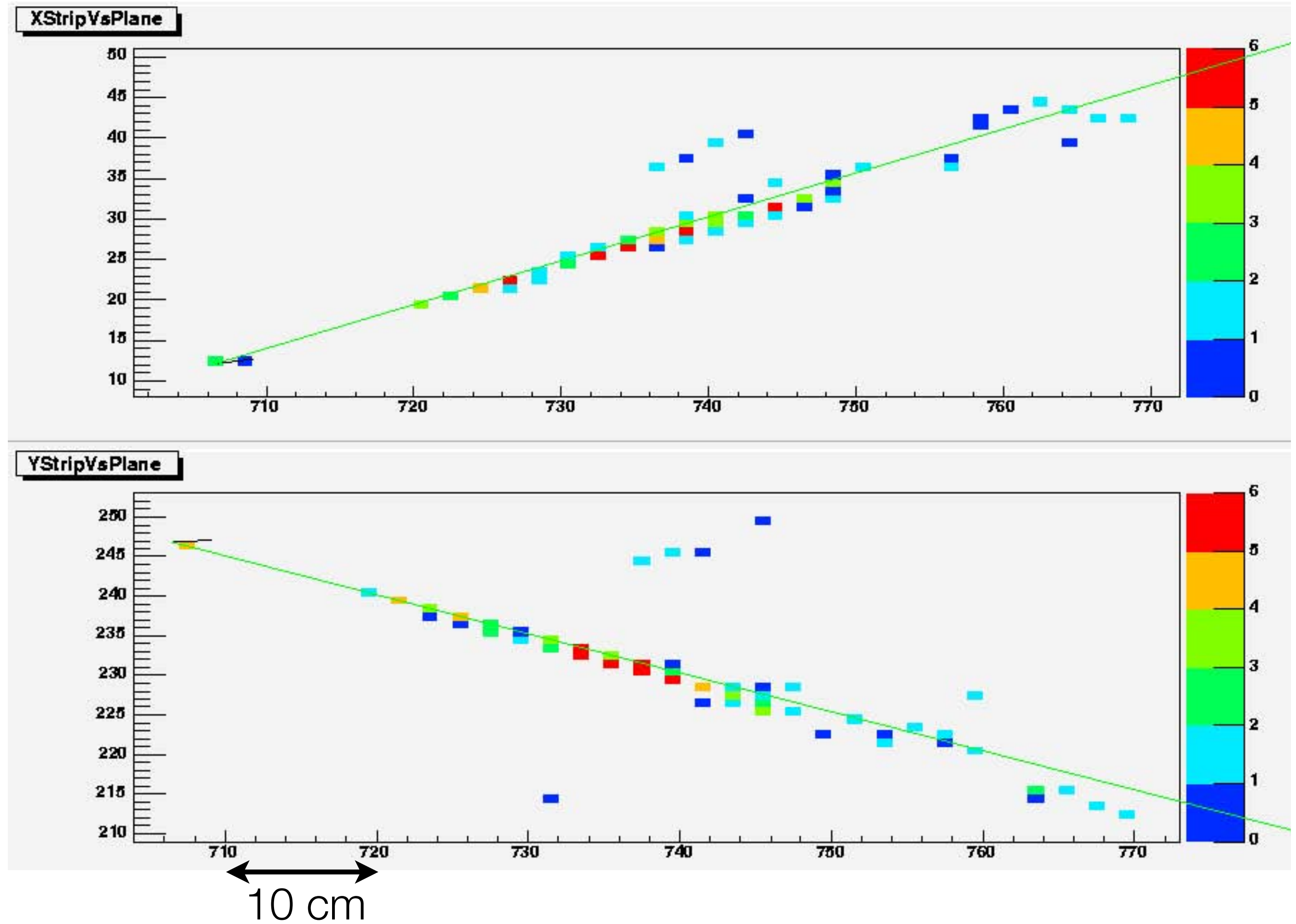
Electron neutrino signal event

Electron and pion tracks reconstructed

Sample signal and background events in NOvA



Sample signal and background events in NOvA

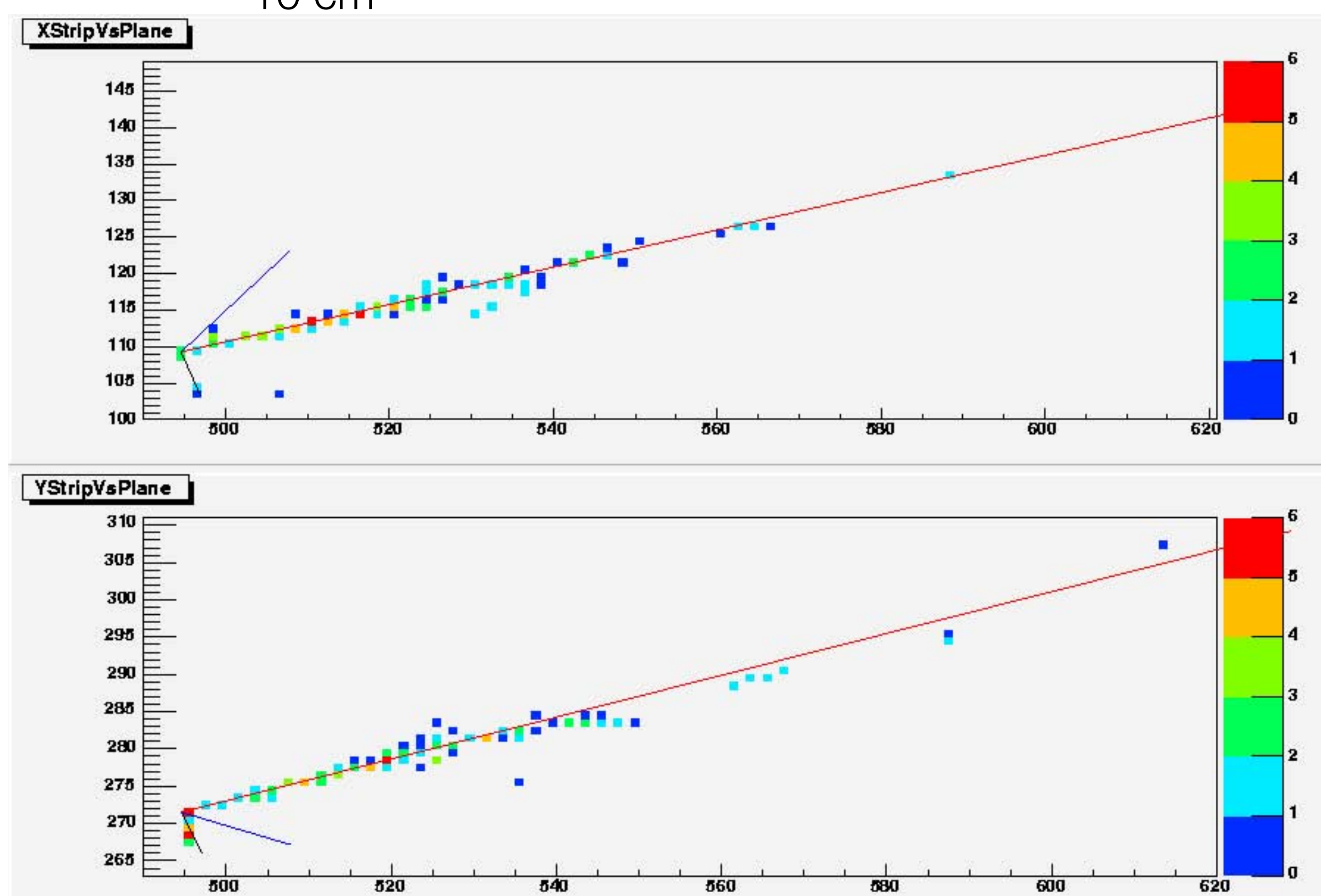


$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

E_ν=10.6 GeV

E_p=1.04GeV

$E_{\pi o}$ =1.97GeV



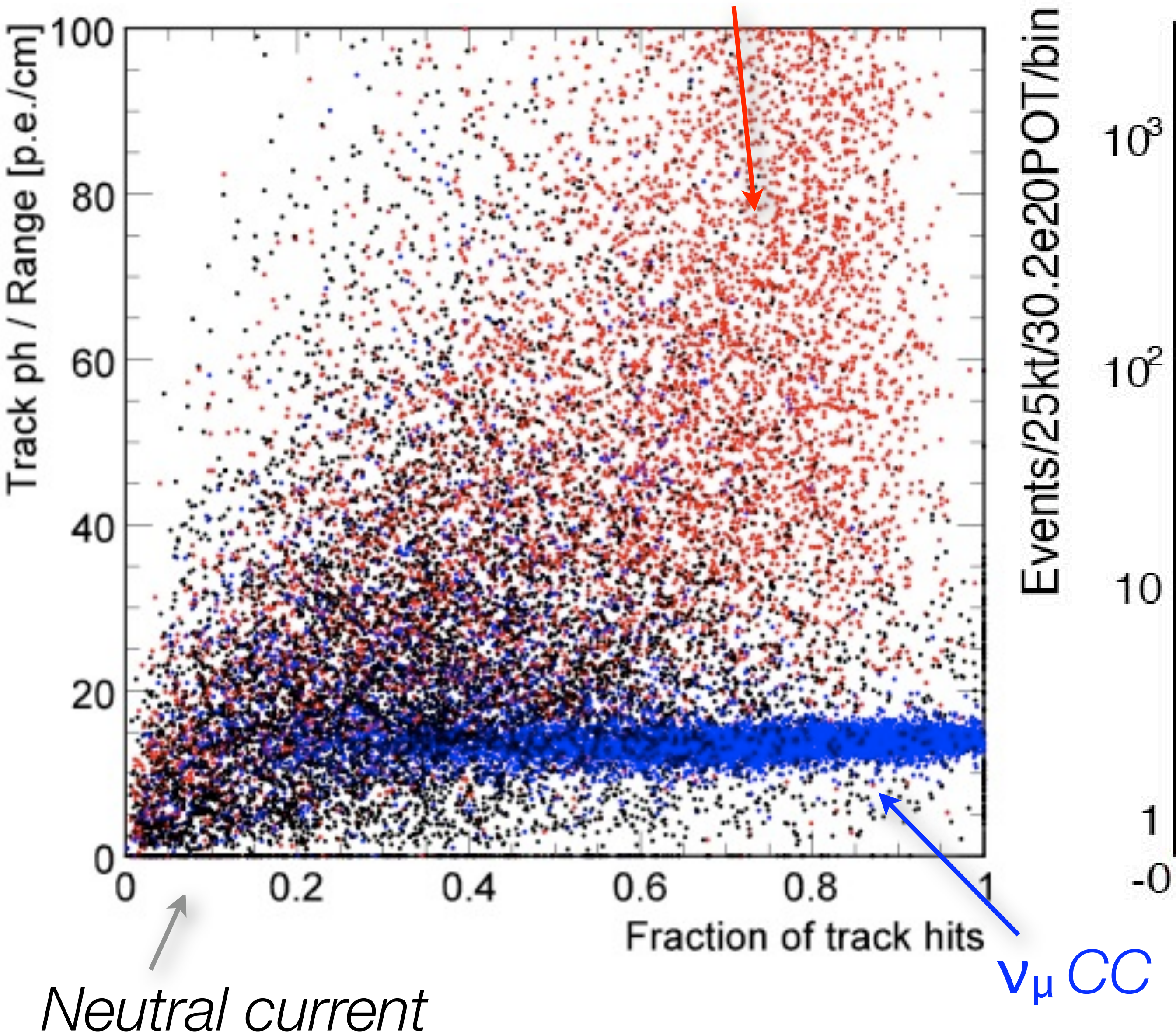
$\nu_e p \rightarrow e^- p \pi^+$

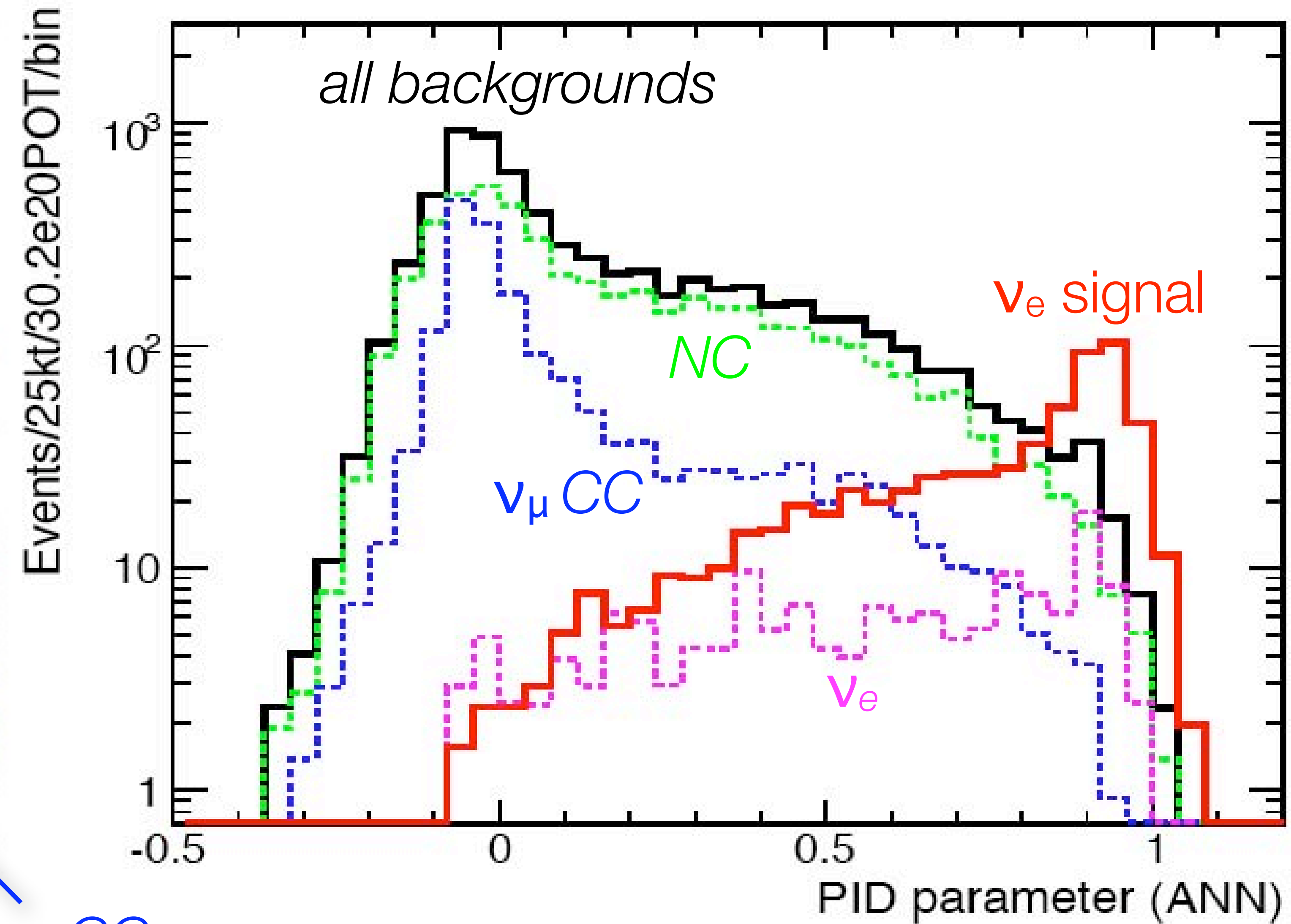
E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

E_π=0.2GeV





Particle ID

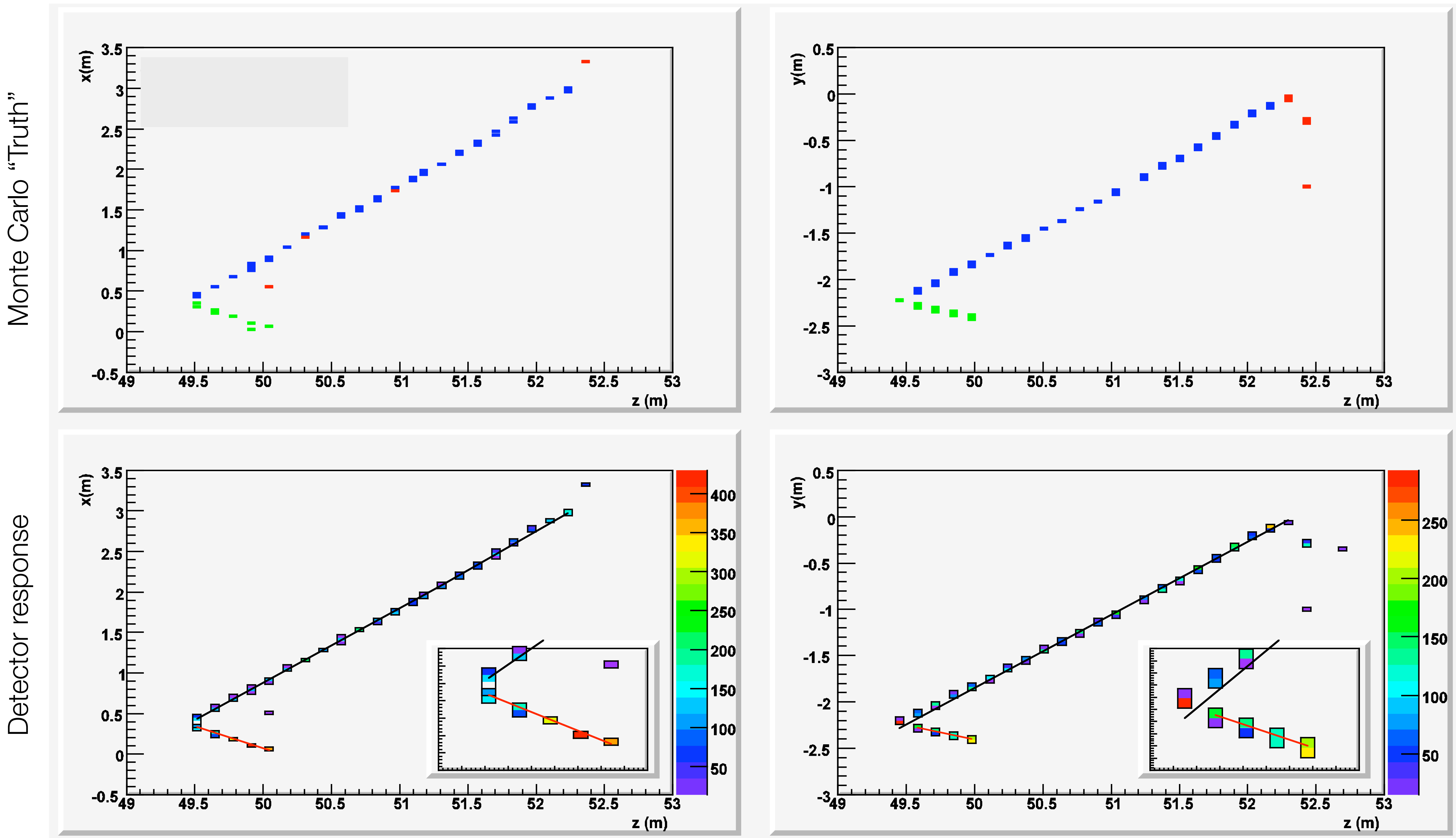
21 event shape variables input to artificial neural net

	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 $\Delta m_{32}^2 = 0.0024\ eV^2$

Event selection

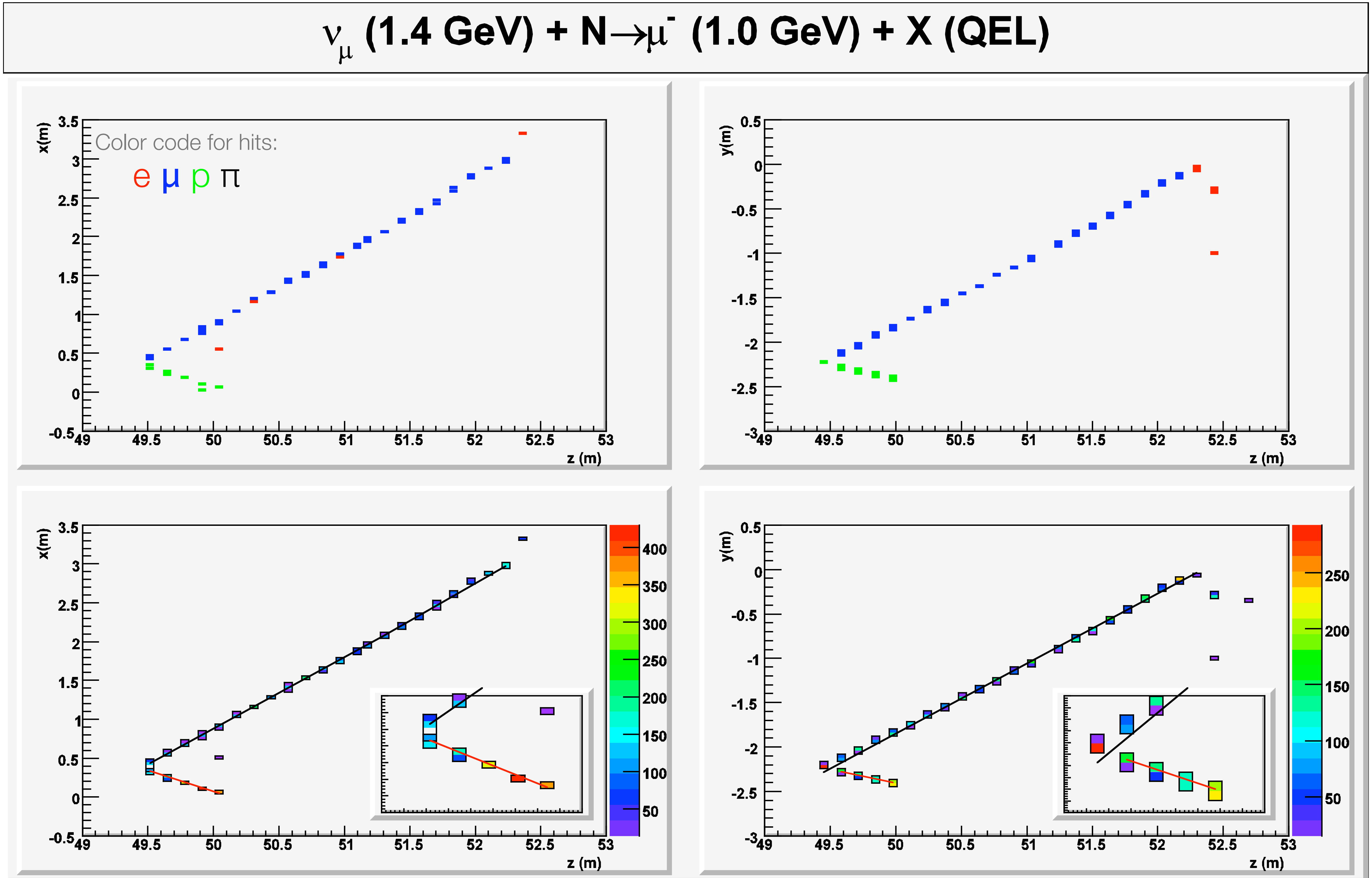
Calculations based on $\sin^2 2\theta_{13}=0.1$ with matter effects turned off. 2 GeV NBB beam.



Monte Carlo "Truth"
Detector response
x(m)
y(m)
z (m)
49
49.5
50
50.5
51
51.5
52
52.5
53
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
400
350
300
250
200
150
100
50

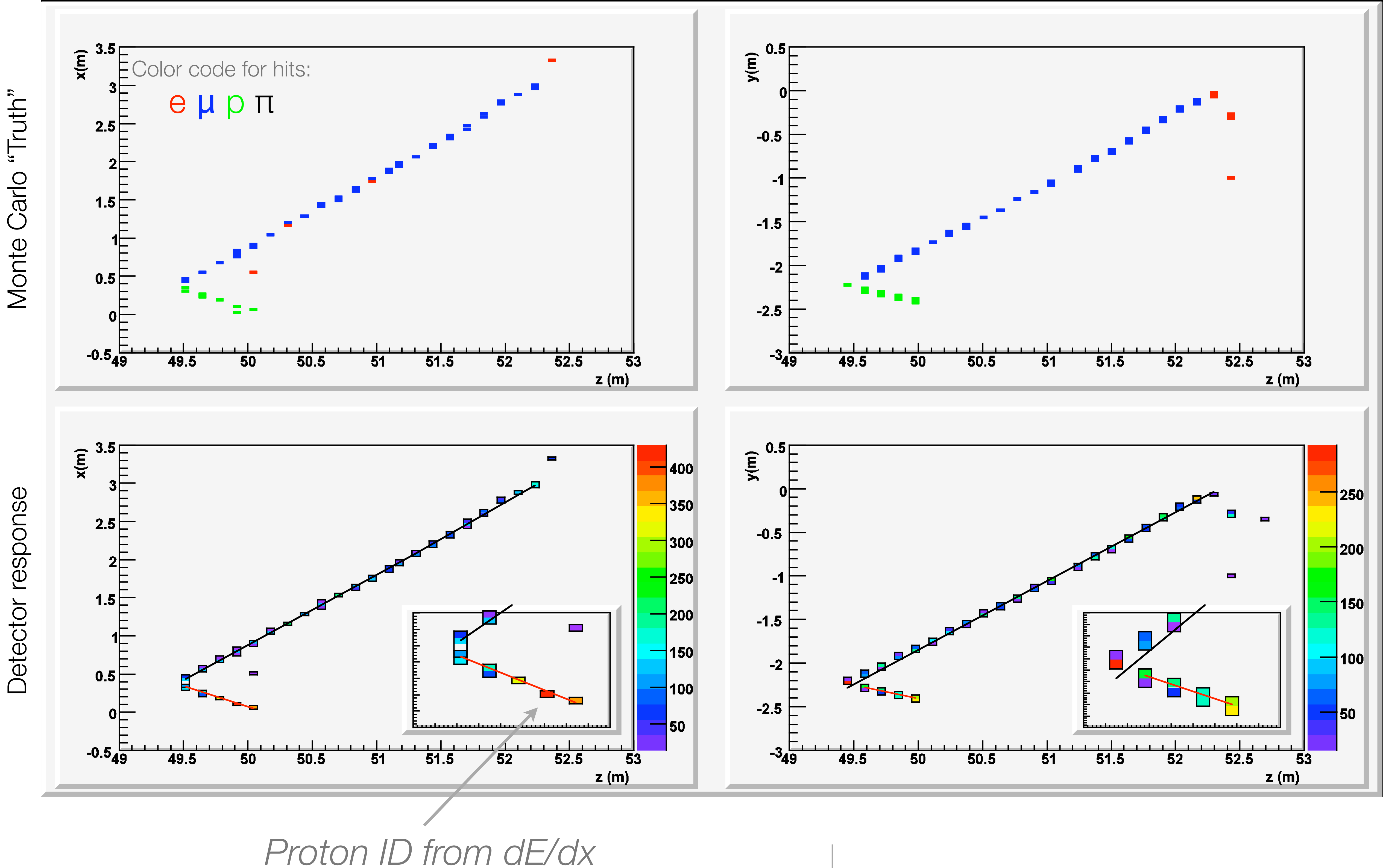
Monte Carlo "Truth"

Detector response



ν_μ Quasi-Elastic Event

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



ν_μ Quasi-Elastic Event