Cross Section Measurements (Detectors)

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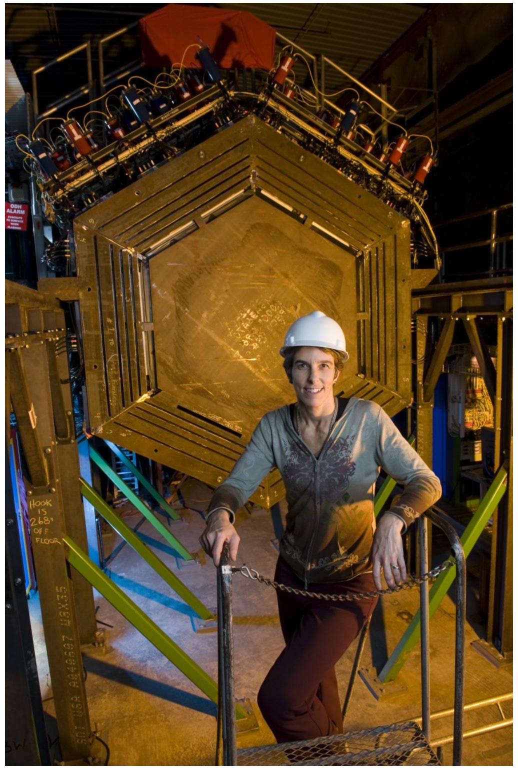
“Experimental” Lectures related to Cross Sections

- Statistics: Lukas Koch
- Systematics for Oscillation Experiments: Clarence Wret
- Neutrino Fluxes: Megan Friend
- Event Generators: Stephen Dolan and Luke Pickering

- Cross Section Measurements (Detectors): Yours Truly
  1. How to make a cross section measurement
  2. Tricks of the Trade: how to use your own data to make a reliable cross section measurement

Who am I?



- This is the end of my fifth year as a prof at York U., with a joint appointment with Fermilab.
- Before that, I worked 20 years as a Scientist at Fermilab
- Before that, I was a postdoc for U of Rochester, also doing a neutrino experiment at Fermilab
- Before that, I was a grad student at U of Chicago, working on a Kaon Experiment at Fermilab
- Have seen different aspects of particle physics:
  - Graduate thesis looking for CP-violation in rare Kaon decays
  - Spent postdoc years studying weak interactions with high energy (~100GeV) neutrinos
  - Started working on neutrino oscillations (~GeV neutrinos)
    - Initially worked on neutrino beam designed for MINOS
    - Started worrying about neutrino interactions-enter MINERvA!
    - Collaborator on T2K & DUNE

Quick soapbox

- There is a lot that goes into cross section measurements
- Papers don't always have enough space to describe those details
- These lectures are meant to explain how to measure a cross section, and the detectors that are currently being used
- Even if you don't measure a cross section yourself, I hope to give you tools to know what a detailed cross section publication *should* be talking about
- Morals of this story:
    - Every measurement has backgrounds
    - No detector is perfect
    - No cross section model is perfect
    - But there are ways to ensure your cross section measurement is valid anyway!

https://www.theguardian.com/science/blog/2014/jun/27/women-scientists-soapboxes-london-south-bank-soapbox-science

Top ten reasons to measure cross sections

1. To understand the weak interaction
2. To understand the structure of the nucleus
3. There is lots of non-perturbative QCD here, it is not something that is calculable from first principles, need data
4. To improve precision in neutrino oscillation experiments
5. You can't find Beyond the Standard Model Physics until you account for the standard model neutrino interactions!
6. You need to predict the backgrounds to your dark matter experiment
7. You get to be involved with all the parts of an analysis
8. Your measurement may get used by lots of other experiments

Reason 9: it makes an awesome thesis topic!

- Even if you ARE on an oscillation experiment, there's some chance your thesis will be a neutrino cross section measurement
- NOvA: https://novaexperiment.fnal.gov/theses/
  - 13 out of 63 Doctoral Theses were on cross sections
- T2K: https://t2k.org/docs/thesis
  - 57 out of 138 PhD+Masters theses have been on cross sections!

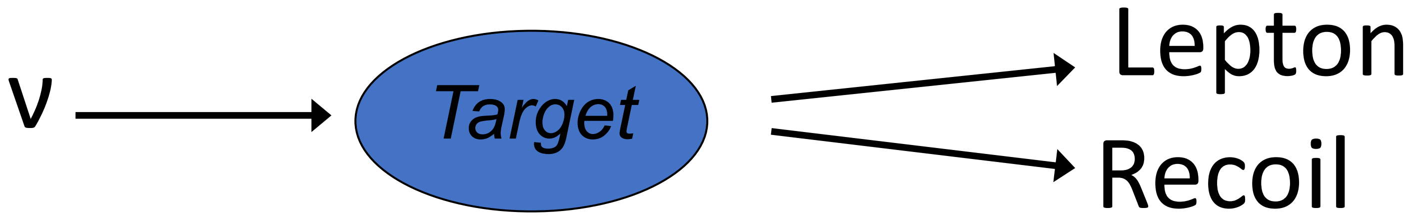
As of August 12, 2023

	Dates	Source	Primary Energy (GeV)	P [kW]	M [kt]	L [km]	E [GeV]
K2K	1999 - 2004	KEK PS	12	5.2	22.5	250	0.9
T2K	2010 - present	JPARC	30	515	22.5	295	0.6
T2HK	2027	JPARC	30	[500,1 300]	188	295	0.6
MINOS	2005 - 2012	Fermilab Main Injector	120	240	5.4	735	3.6
MINOS+	2013 - 2016	Fermilab Main Injector	120	700	5.4	735	6.2
NOvA	2014- present	Fermilab Main Injector	120	400 - 960	14	810	1.8
DUNE	>2030	Fermilab Main Injector	120	1000 - 2400	40	1350	2.2
CNGS / OPERA	2008 - 2012	CERN PS	400	512	1.25	730	1.25

From Mark Messier, INSS23

Reason 10: to learn more about neutrinos

- *Quick wakeup question: what can we learn about neutrinos WITHOUT seeing them interact?*
- Creation of that final state may require energy to be transferred from the neutrino



  - In charged-current reactions, where the final state lepton is charged, this lepton has mass
  - The recoil may be a higher mass object than the initial state, or it may be in an excited state

K. McFarland, INSS 2013

What exactly does “cross section” mean?

- Wikipedia sez: (cross section-physics)
    - A Cross Section is a measure of the probability that a specific process will take place in a collision of two particles.
    - It can be thought of as the size of the object that the excitation must hit in order for the process to occur

- How would you measure this?
    - Think about throwing darts at a dartboard
    - How would you measure the size of the bullseye? (for random throws)

How to measure a Cross Section

- Let's deconstruct that sentence: number of darts that you are throwing per unit area: flux $\Phi_\nu(E_\nu)$
- Fraction of time you actually measure that the dart hit the target per number of times it did hit the target $\epsilon(E_\nu)$
- Number of dartboards: M

$$N(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)M$$

Mass (number of targets)

Interaction cross section (area per target)

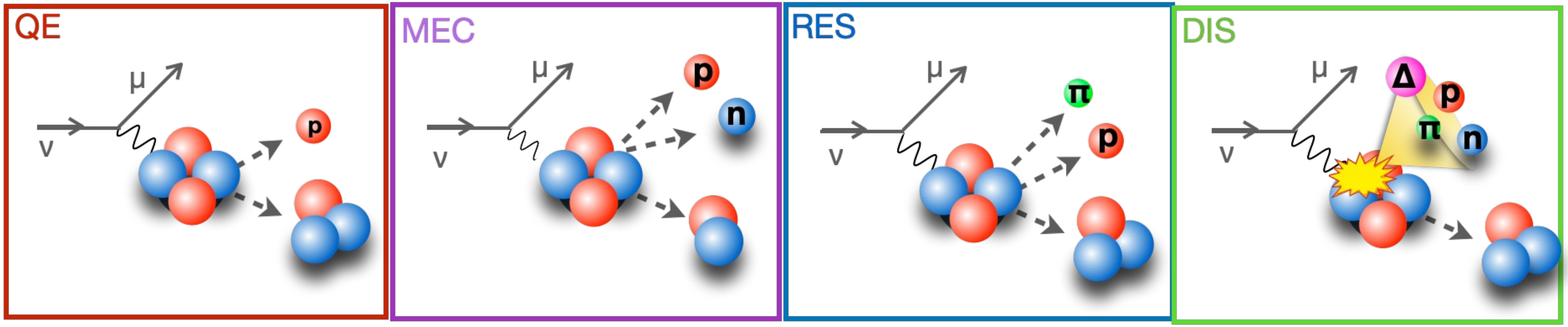
Neutrino flux (ν's per unit area)

Detector effects, use event generator to estimate this

What particles do we need to measure?

$$\frac{d\sigma}{d\Omega dE'}$$

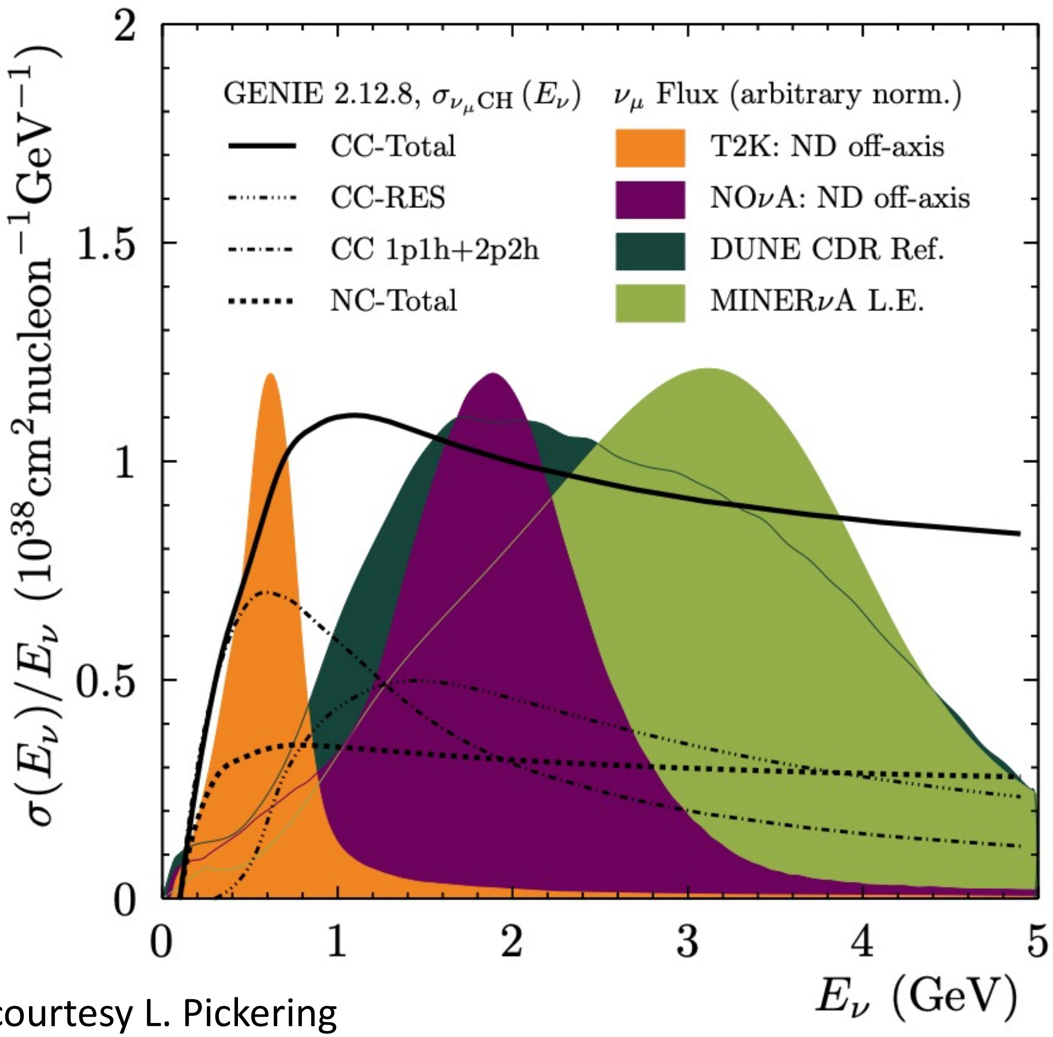
- Electron Scattering measurements:
  initial and final energy of electron, and the scattering angle
- Neutrino Scattering measurements: need to measure lepton AND final state hadrons to measure energy transfer



From N. Rocco

What are the energies we'll see?

- Consider current collection of neutrino beams available:
- Need to become experts in interactions of few 100 MeV to few GeV particles
  - Muons
  - Electrons
  - Protons
  - Charged pions
  - Photons
  - Maybe a few kaons or Λs?

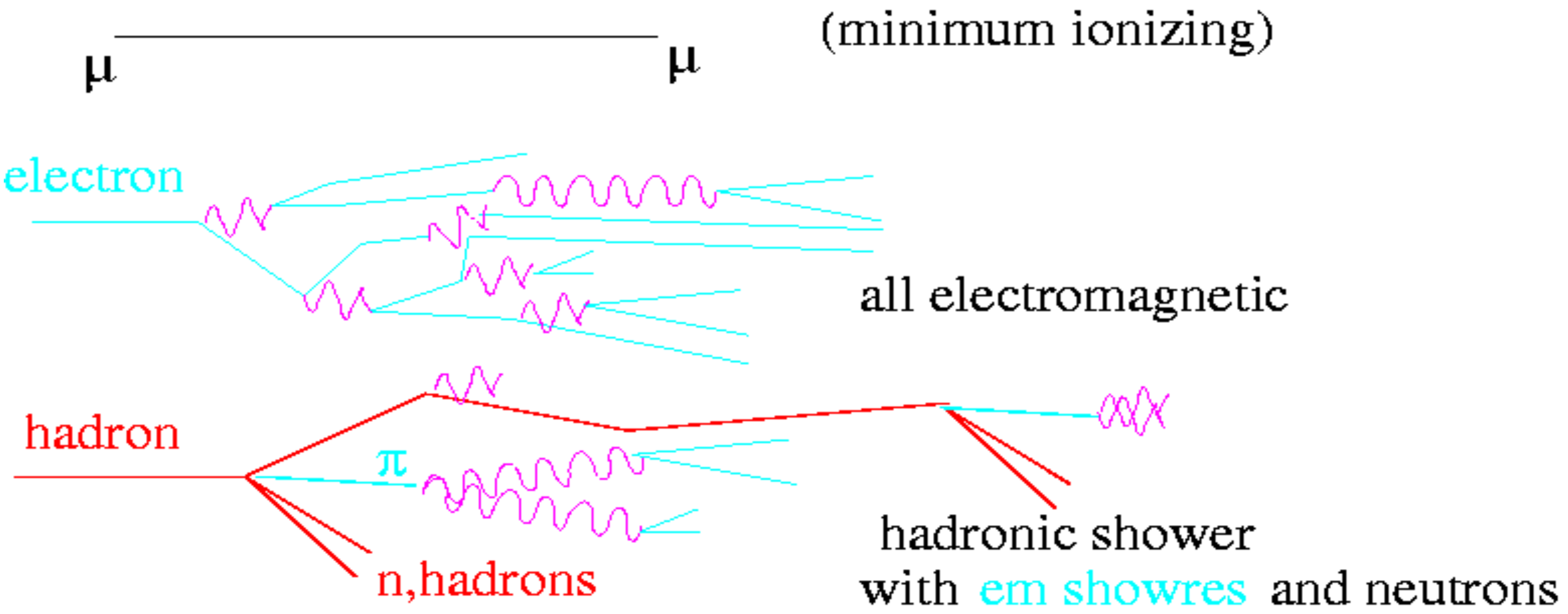


Plot courtesy L. Pickering

Detector Fundamentals

- Particle interactions in matter
  - Energy loss by ionization
  - Electromagnetic Showers
  - Hadronic Showers
- Detectors
  - Water Cerenkov
  - Segmented Scintillator
  - Liquid Argon
  - Active/Passive Calorimeter

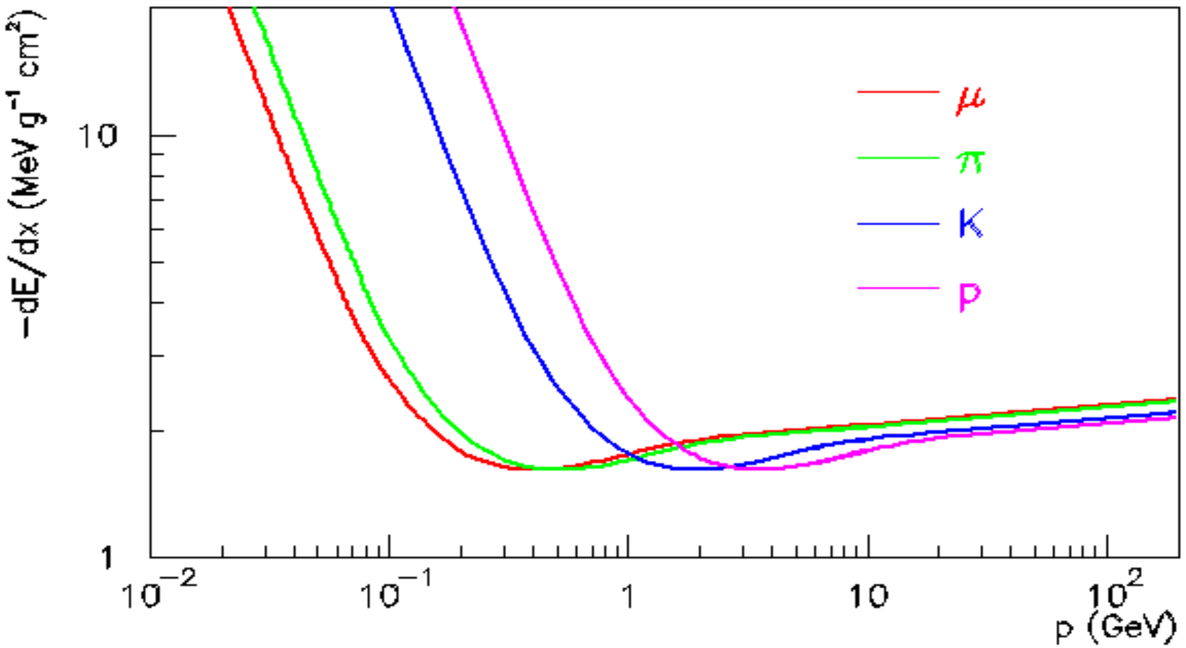
Three kinds of particle signatures



- 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 charged particle does not shower, it loses energy through ionization
  - For Hadron: range<λ_{INT}
  - For Electron: range<X_0



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

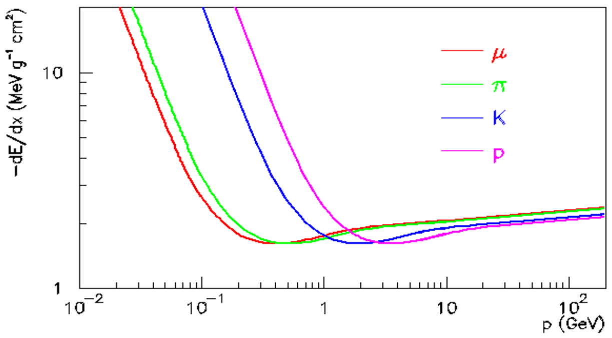
- Bethe-Bloch Equation
- Typical value: 2MeV*cm^2/g
- *x* in units of g/cm^2
- Energy Loss Only f(β)

- Can be used for Particle ID in range of momentum

dE/dx in common detector materials

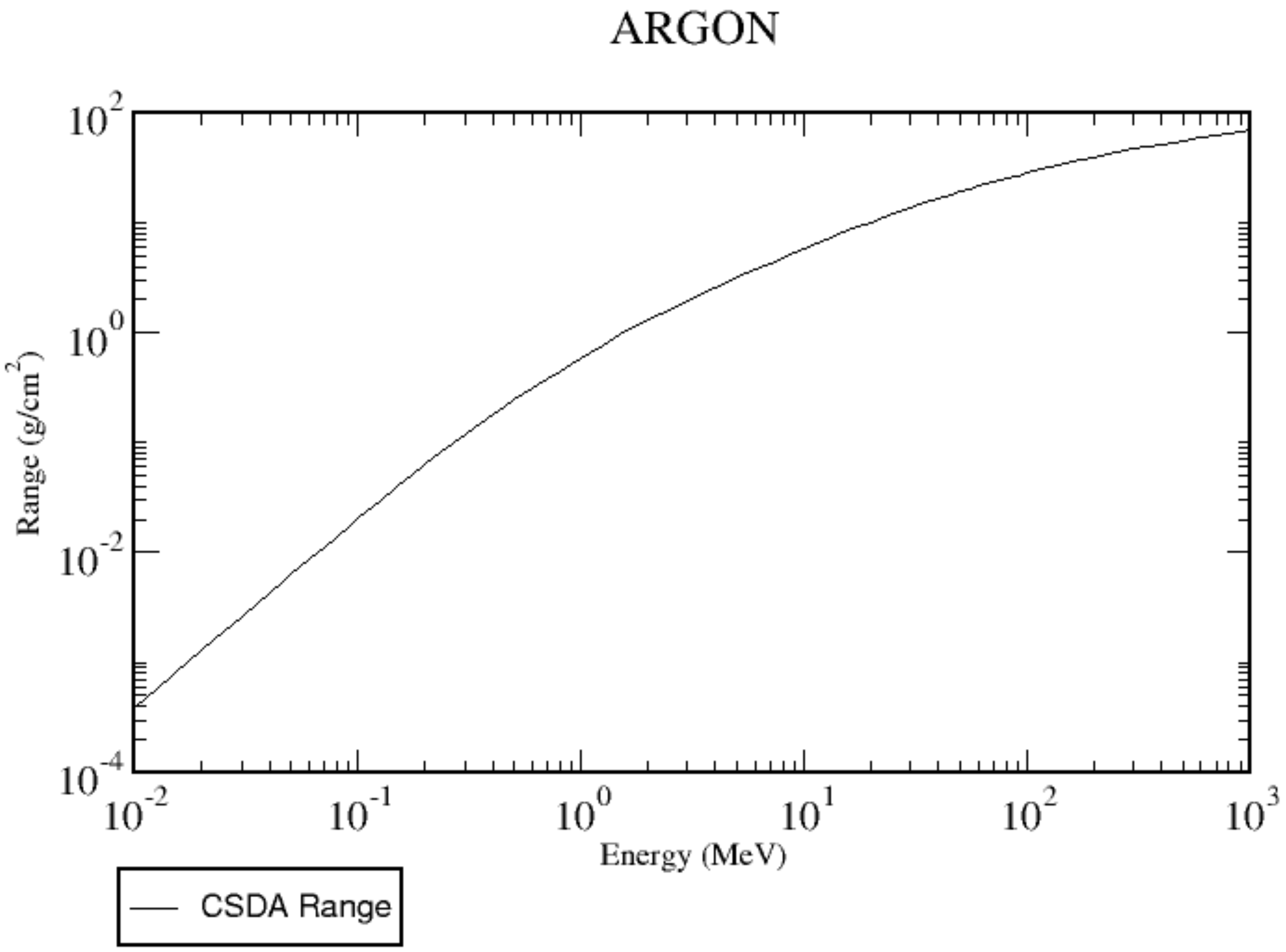
- These values determine how long an event will be in one's detector
- Determines how big the detector might need to be
- Example: T2K: to contain a 700MeV muon, need ~350cm of water or scintillator, ~65cm of steel

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



Handy Reference

- Range for electrons and protons in material:
  - https://www.nist.gov/pml/stopping-power-range-tables-electrons-protons-and-helium-ions
  - Graph shown below for electrons in argon: multiply by density to get distance
  - Tables also provided

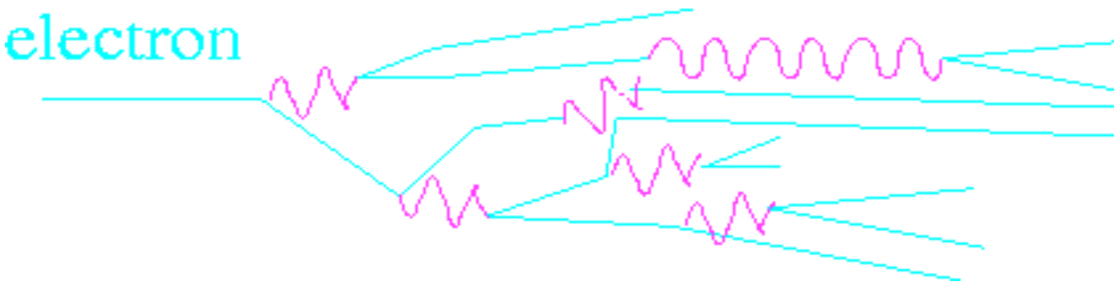


Homework question #1:

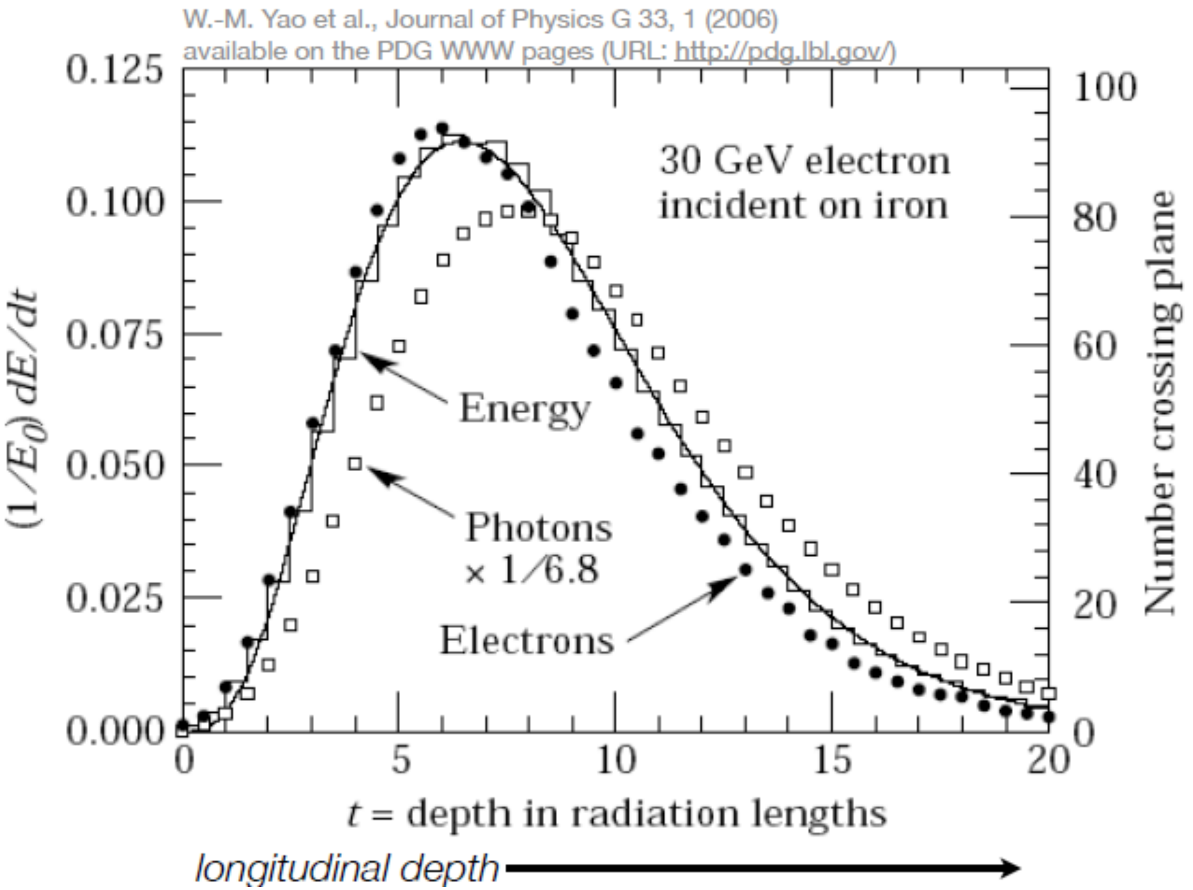
- How far does a proton with 100MeV Kinetic Energy go in
  - Plastic Scintillator (could consider C alone)
  - Iron
  - Argon
- How far does a muon with 2000 MeV Kinetic Energy go in
  - Plastic Scintillator
  - Iron
  - Argon

Can also use reference: http://pdg.lbl.gov
Atomic and nuclear properties of materials
To get dE/dx_{min} in units of g/cm^2

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



$$E_c = \frac{800MeV}{Z + 1.2}$$

Shower Maximum: $$t_{max} = ln\left(\frac{E_0}{E_c}\right) + C_i$$

C_e = -0.5, C_γ =0.5

Homework question #2:

- What is the shower max (in cm) for a 1GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead
- What is the shower max (in cm) for a 2GeV electron:
  - Plastic Scintillator
  - Iron
  - Argon
  - Lead

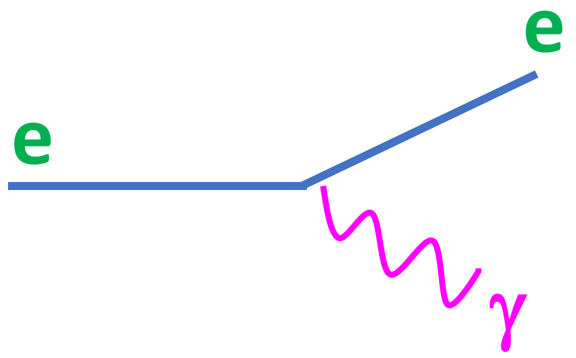
Radiation Length

- 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

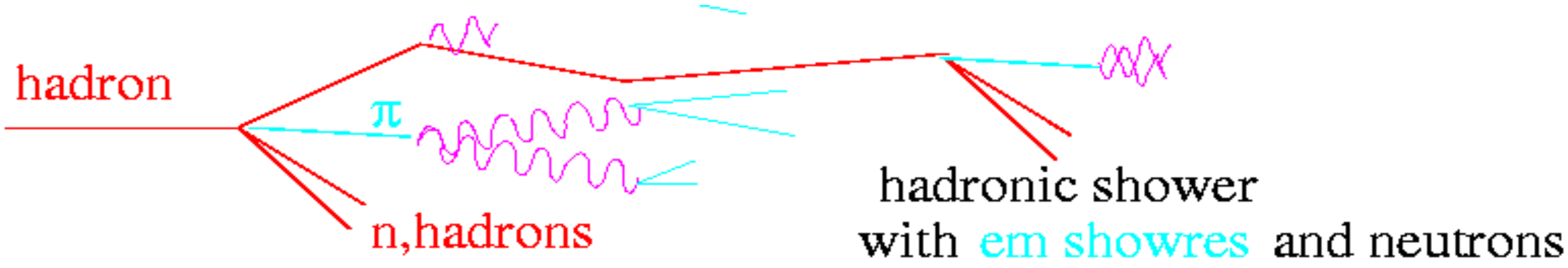
$$R_M = X_0 \frac{21.2\ \text{MeV}}{E_C}$$



Material	X_o (cm)	Z
Liquid Argon	14	18
Water	37	8+1
Steel (Iron)	1.76	26
Scintillator (CH)	42	6+1
Lead	0.56	82

Hadronic Showers

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



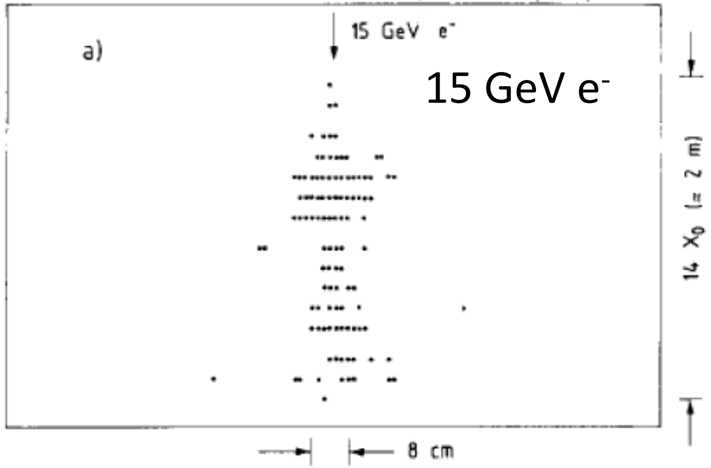
- Instead of a radiation length, now there is an interaction length, λ_I , defined by the average distance a hadron travels before it undergoes a strong (nuclear) interaction
- The catch: sometimes π^0's are produced which decay to photons which then proceed electromagnetically
- Another catch: sometimes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

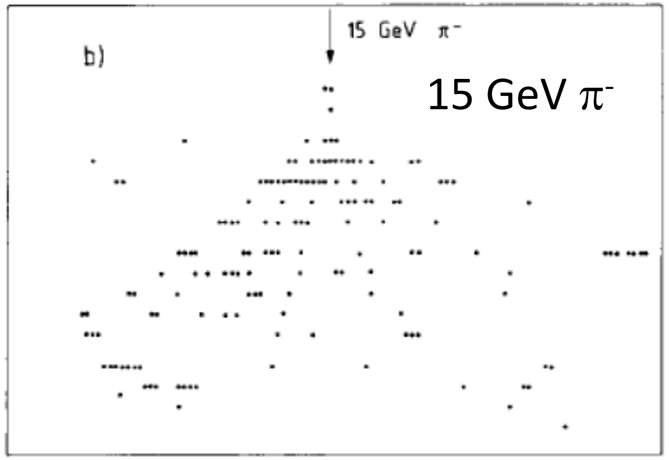
Hadronic vs Electromagnetic Showers

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

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

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





Summary Particles passing through material

Particle	Characteristic Length	Dependence
Electrons	Radiation length (X_o)	Log(E)
Hadrons	Interaction length (l_{INT})	Log(E)
Muons	dE/dx	E
Taus	Decays first	gct=g87mm

Material	X_o (cm)	λ_{INT}(cm)	dE/dx (MeV/cm)	Density (g/cm^3)
Liquid Argon	14	83.5	2.1	1.4
Water	37	83.6	2.0	1
Steel	1.76	17	11.4	7.87
Scintillator (CH)	42	~80	1.9	1
Lead	0.56	17	12.7	11.4

Incomplete Survey of Neutrino Detector Technology

- Cerenkov Detector
  - Water Cerenkov
- Scintillator Detectors
  - Segmented scintillator
- Liquid Argon TPC
- Active/Passive Detectors
  - Steel plus tracker
  - *Emulsion*
  - *Ice*

Focusing on detectors used to measure cross sections

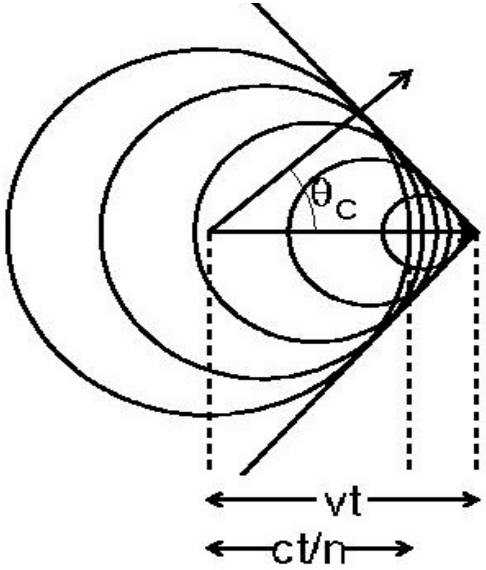
These are often used in combinations for cross sections or near detectors

For Each Detector

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

Cerenkov Detectors

Cerenkov Light



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

$$\beta \equiv \frac{v}{c}$$

$$\beta > \frac{1}{n}$$

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

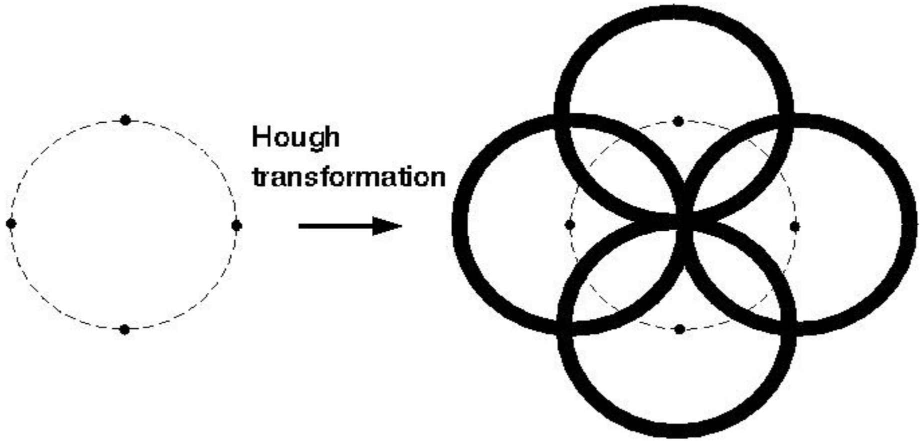
$$p_{threshold} = \frac{m}{\sqrt{n^2 - 1}}$$

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

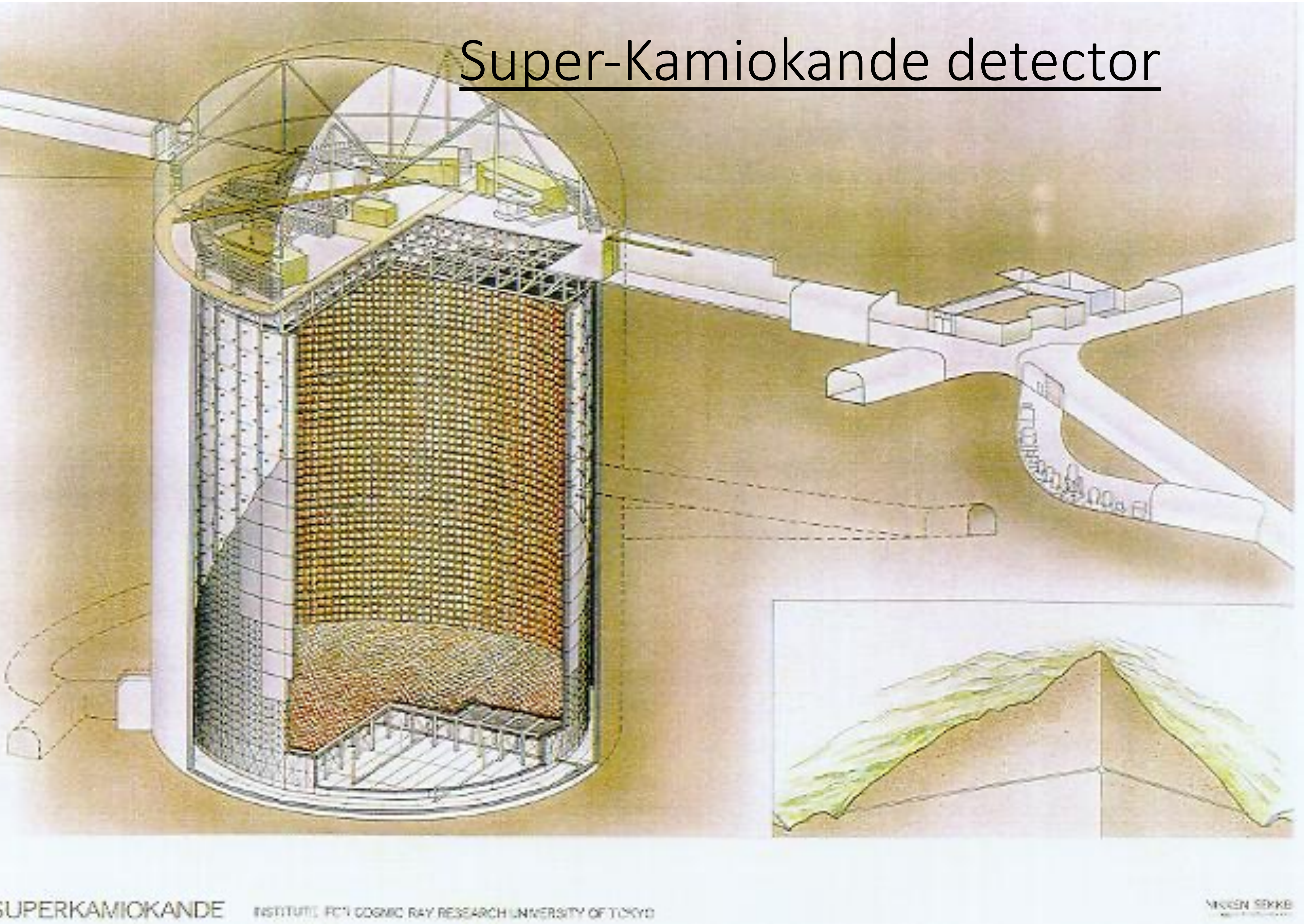
- For water, n(280-580nm)~1.33-6, so $p_{threshold}$≈1.3*mass
- Threshold Angle: 42°
- **What is Threshold momentum for neutral pions?**

Event Reconstruction in Cerenkov Detector

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



Super-Kamiokande detector



50,000 ton water Cherenkov detector

(22.5 kton fiducial volume)

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

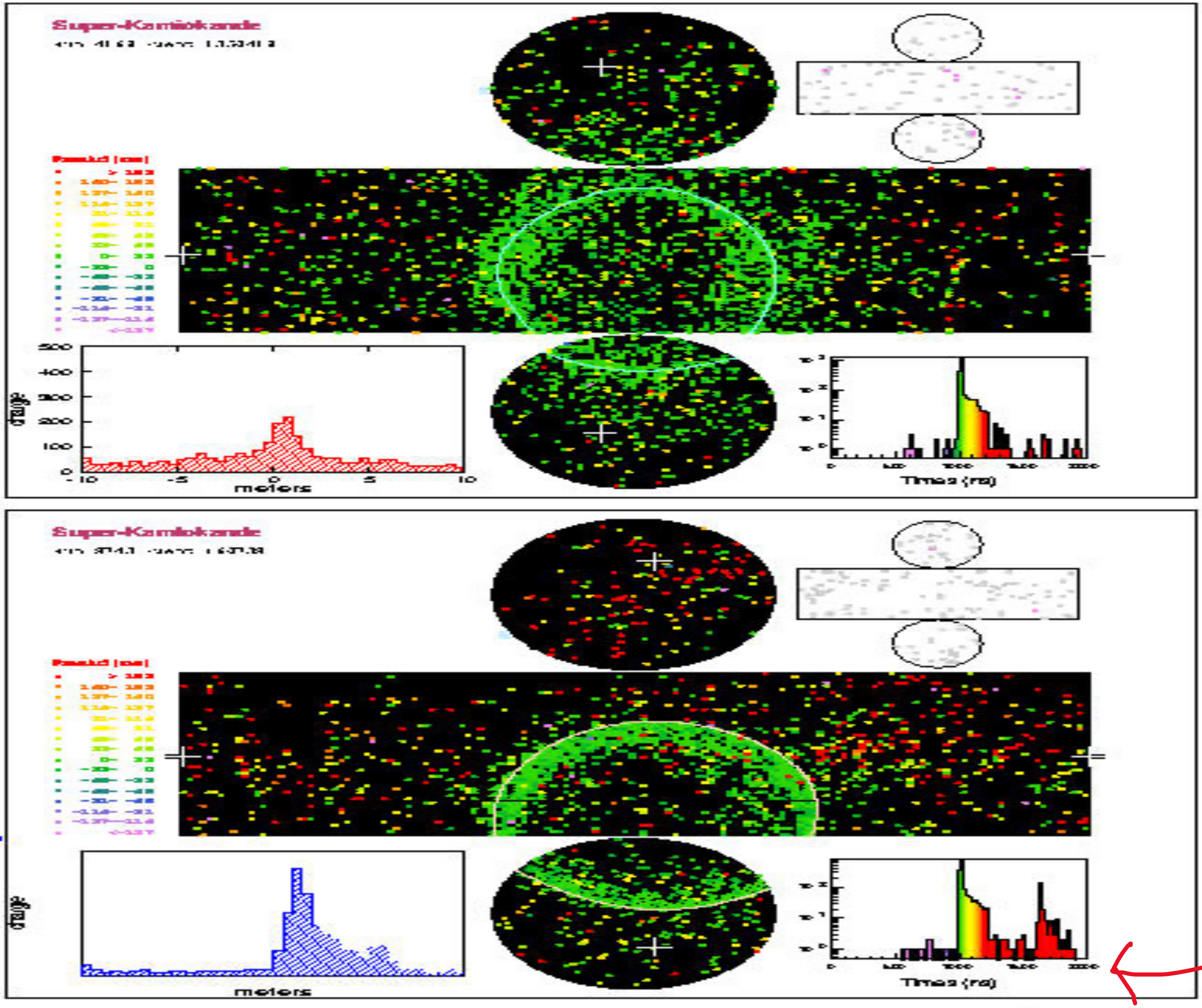
11,146 20-inch PMTs for inner detector

1,885 8-inch PMTs for outer detector

e-like

μ-like

2GeV neutrino interaction



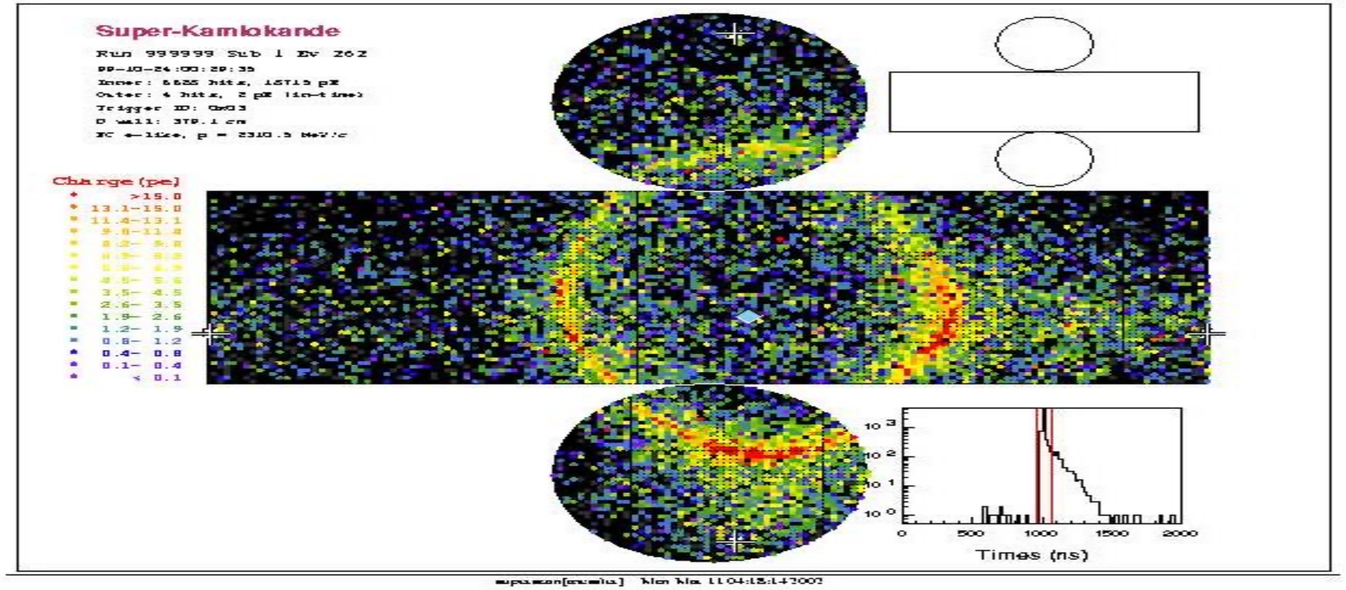
What is this?

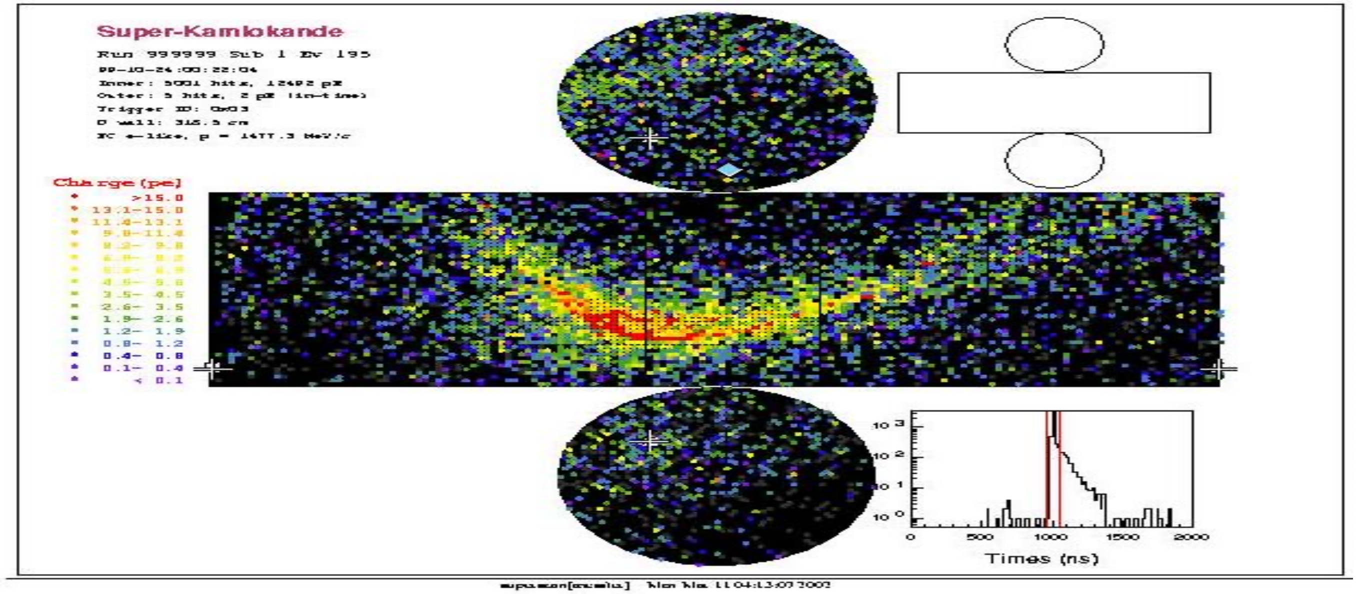
Neutrino Energy Reconstruction

- Homework #3:
  - 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 (don't look this up!)
  - Then look up what T2K uses, it should be close…
- 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 ν_e signal, one is π^0 background

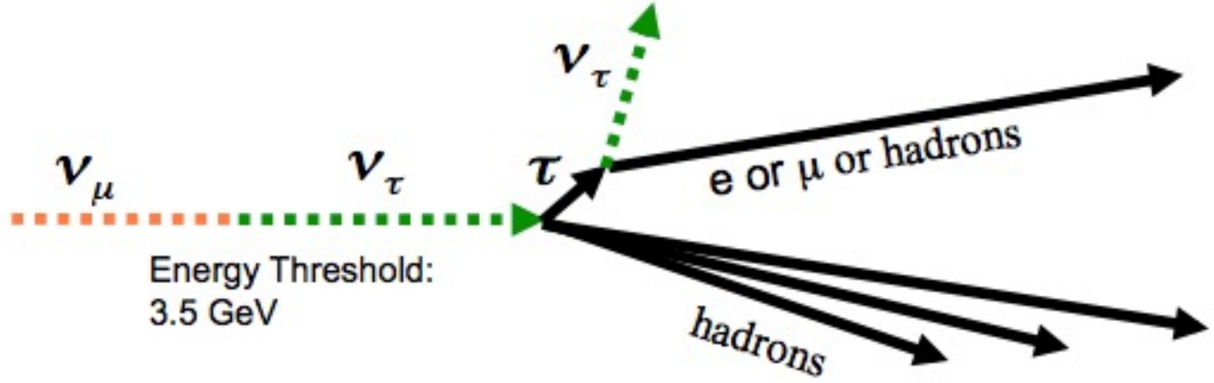


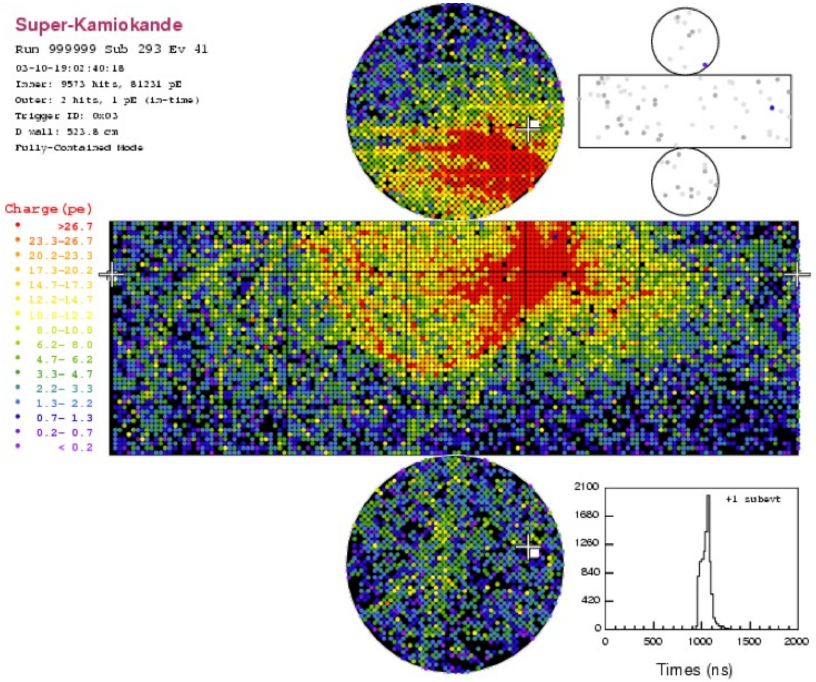


For Visible Energy of 2GeV:
One Is e^-
One Is a π^0

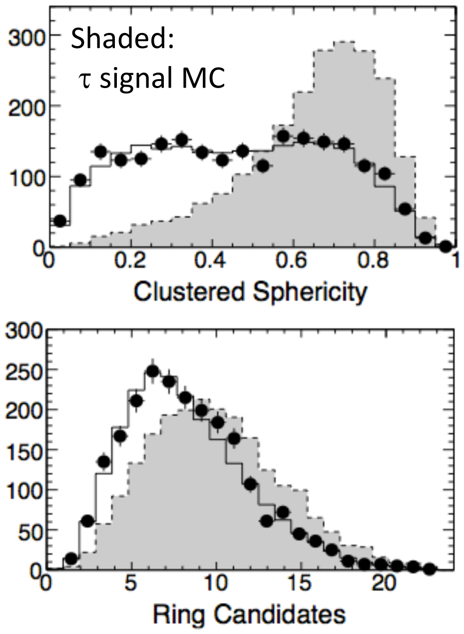
τ neutrinos in Super-K

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



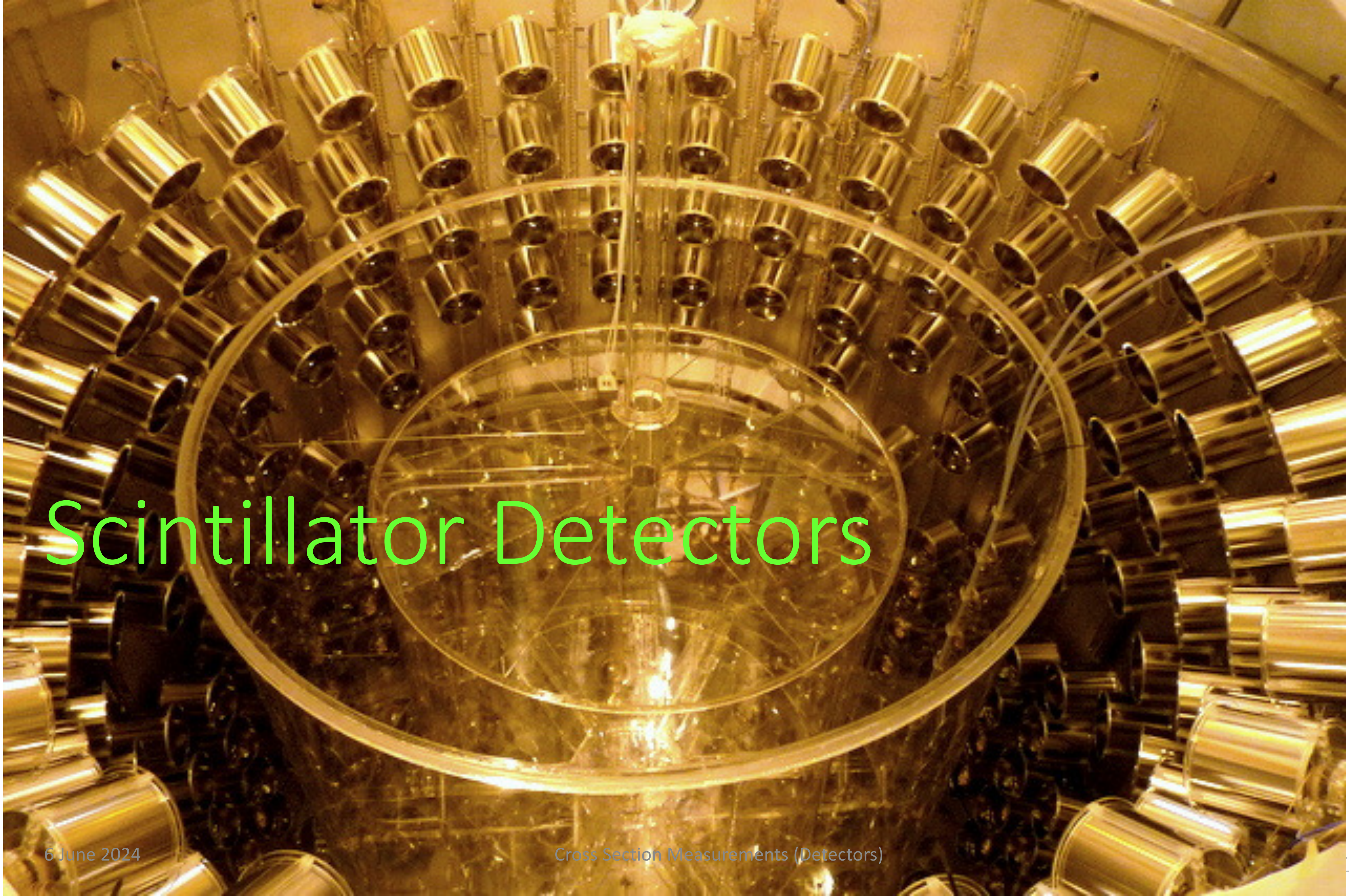


Phys. Rev. Lett. 110, 181802 (2013)

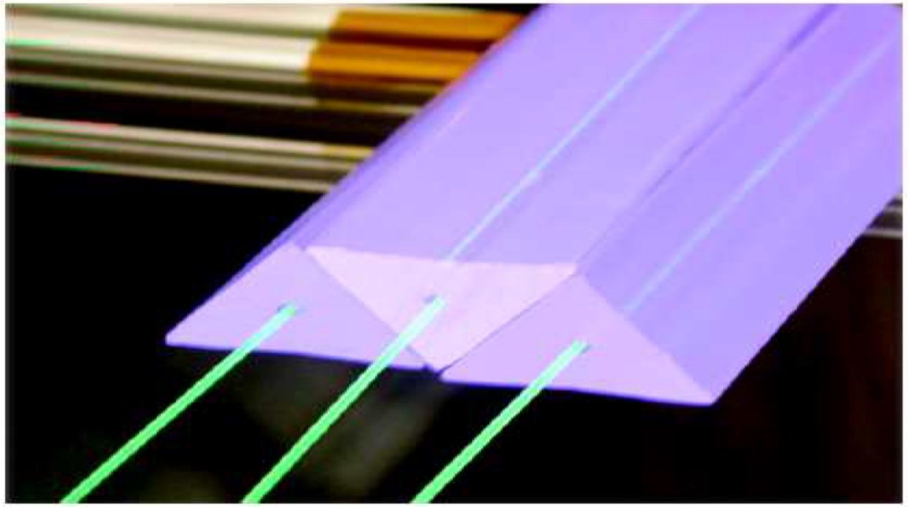


C. Walter, INSS 2012

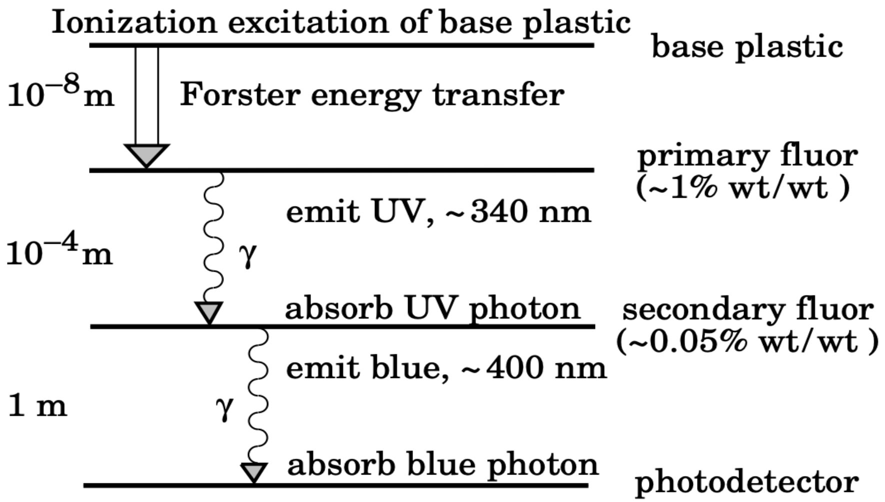
Scintillator Detectors



Scintillation Light



- Idea is very simple.
  - Ionized atoms/molecules are in an exited state and emit light.
  - Use waveshifters to move the light to a frequency where it can travel through the material.
  - Read out at the end with photon detectors.



Particle Data Group "ladder" of scintillation process

Advantages:

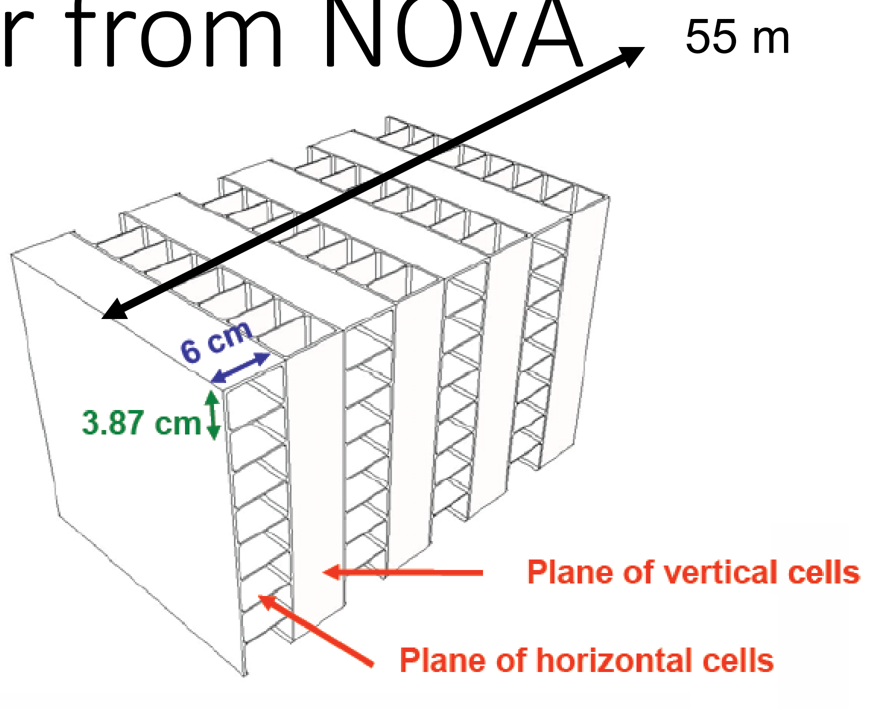
- Fast Response
- Easy to form the shapes you want

Disadvantages:

- signal size is small
- light can saturate

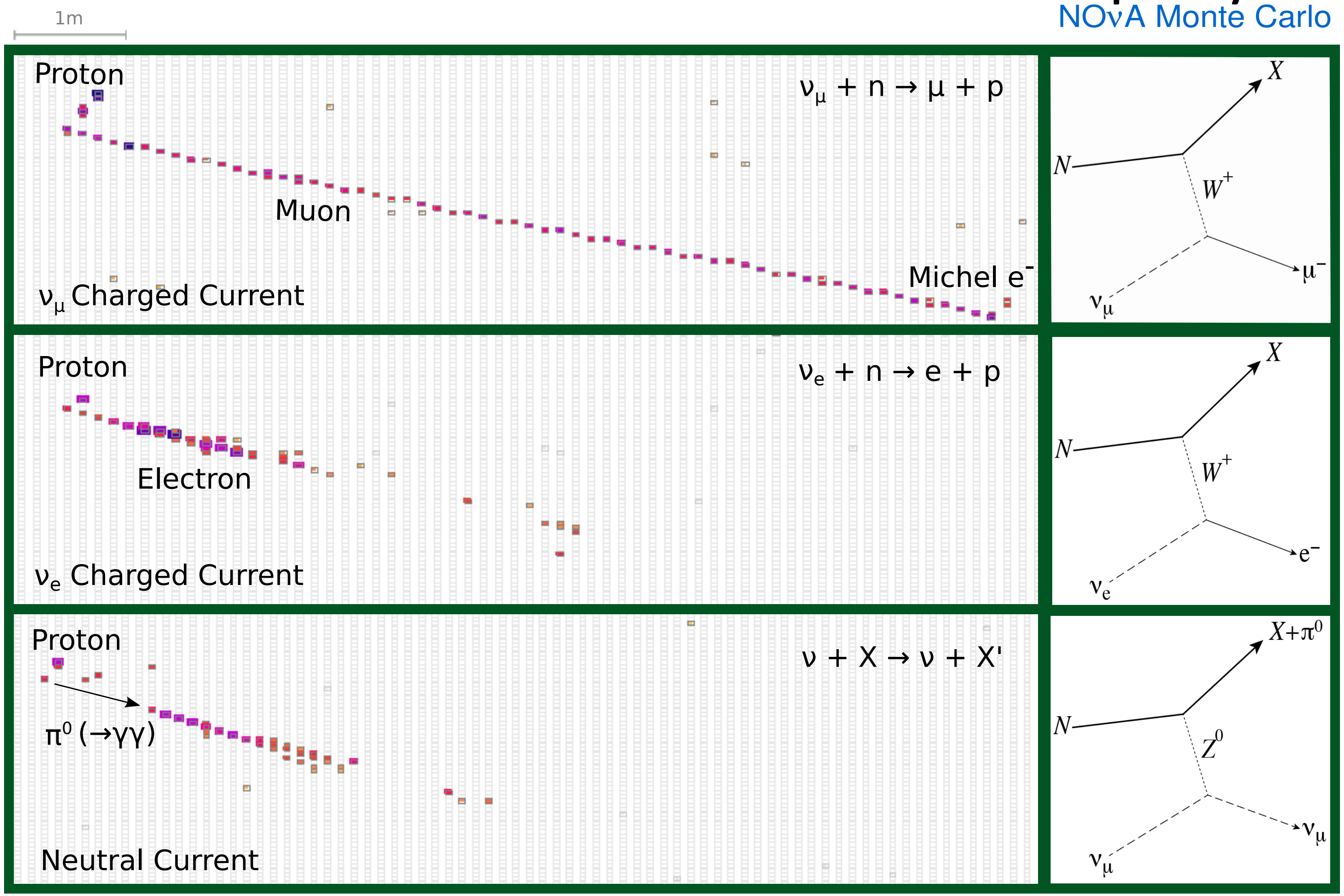
Segmented Scintillator from NOvA

- PVC extrusions
  - 16m tallx16m widex55m long
  - 3.9 cm transverse, 6.6 cm wide in beam direction
- 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 until you run out of money

NOνA Data Event Displays



Near Detector used for cross sections has same cell size, same longitudinal segmentation

Reference:

NOvA: half-time review

DOI: 10.1140/epjs/11734-021-00285-9

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

Detector Volume

- Scaling detector volume is not trivial

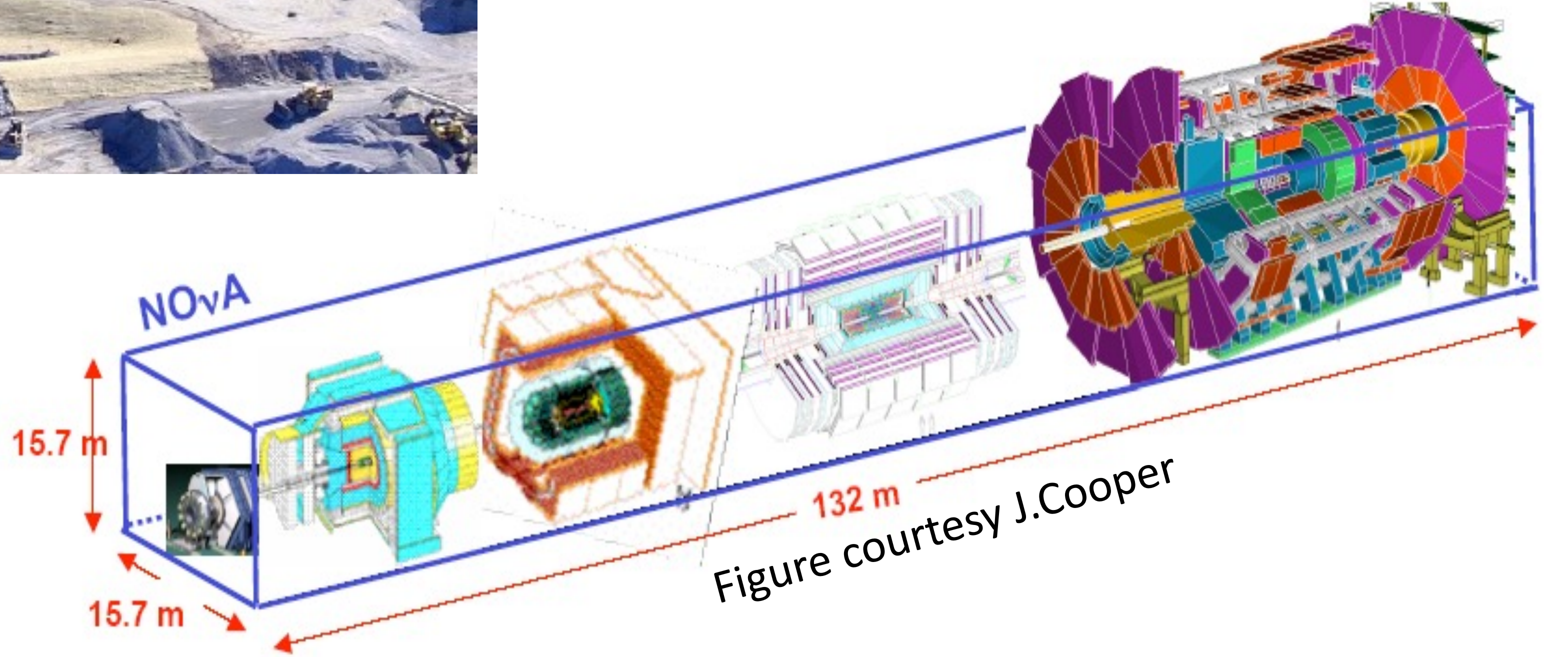
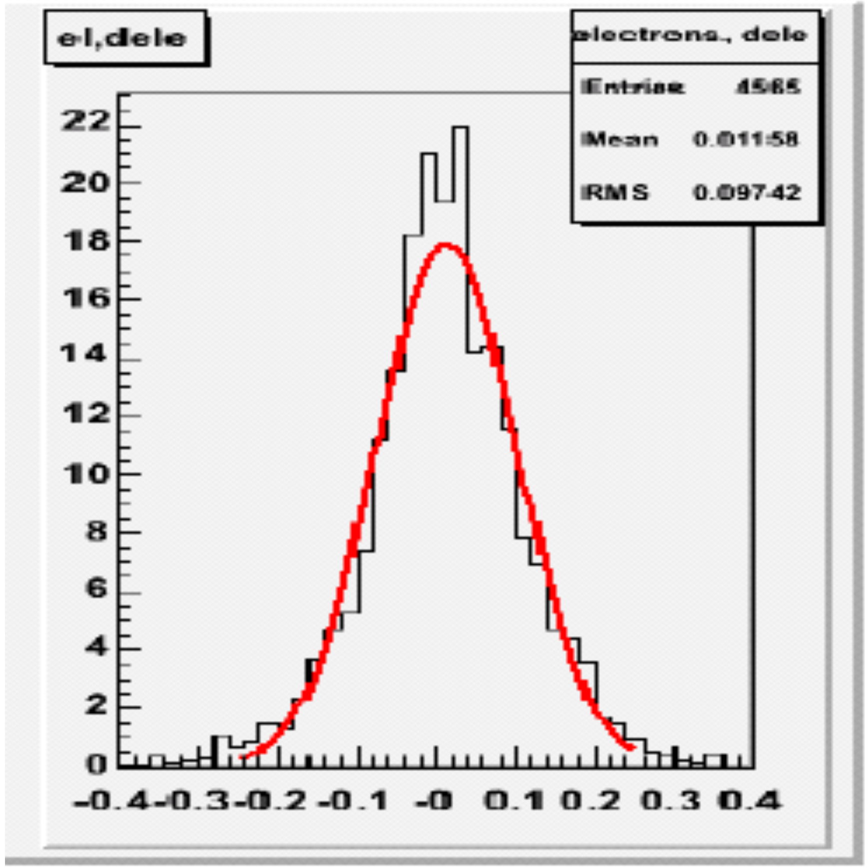


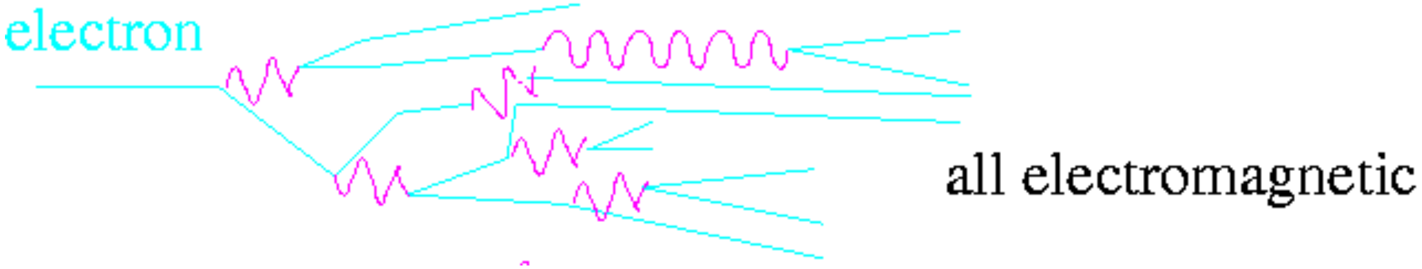
Figure courtesy J.Cooper

Energy Resolution

Energy Resolution



$$\frac{E_{measured} - E_{true}}{\sqrt{E_{true}}}$$



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

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

- Plot at left: ν_e CC events with a found electron track (about 85%),

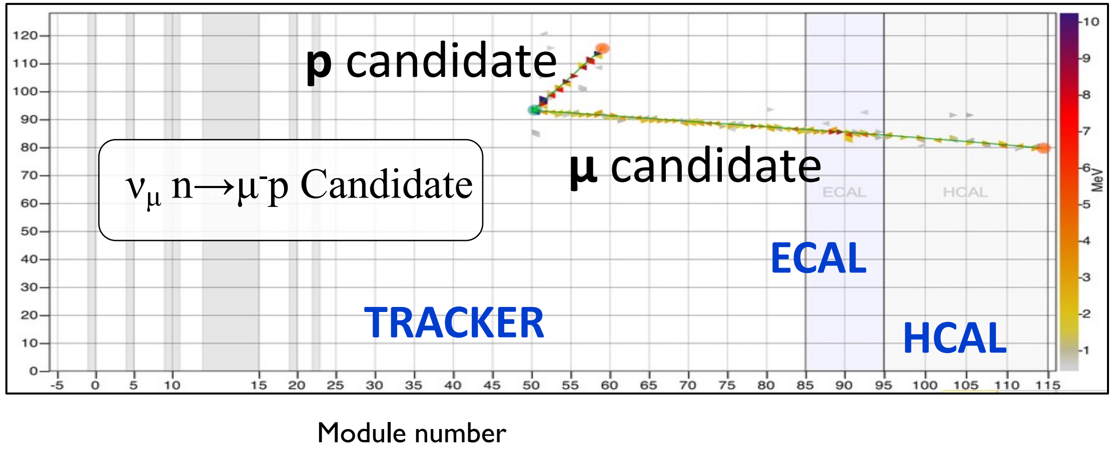
Energy resolution (for neutrinos) is ~ $10\% \times \sqrt{E_{true}}$

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

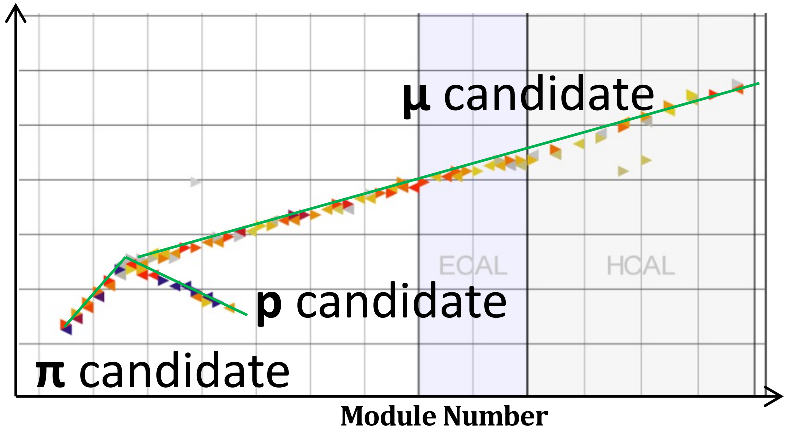
https://arxiv.org/pdf/hep-ex/0503053

Neutrinos in MINERvA (1.7cm/3.3cm granularity)

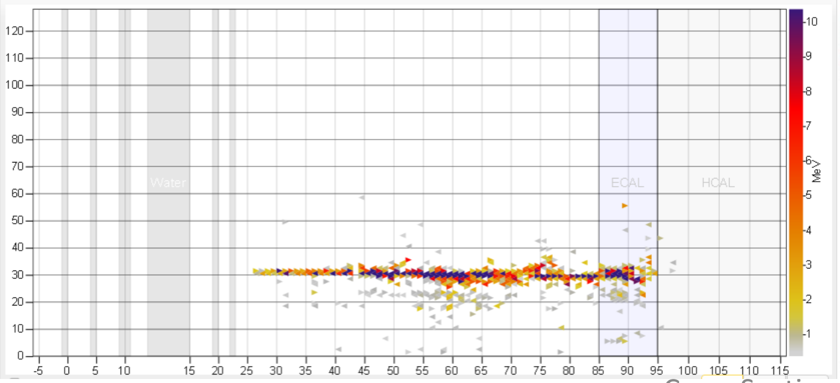
One out of three views shown, color = energy

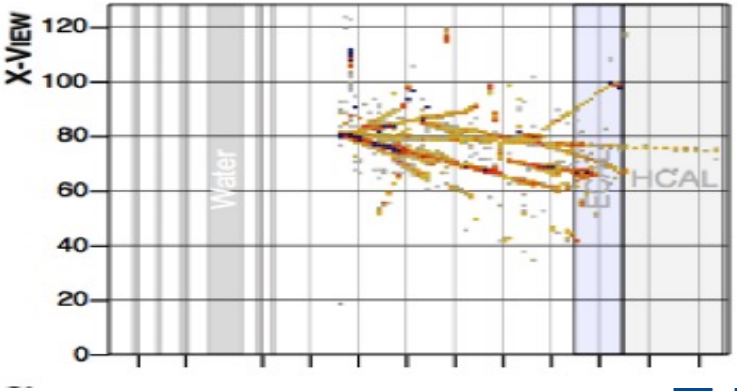


$\nu_\mu\, p \rightarrow \mu^- \Delta^{++}, \Delta^{++} \rightarrow p \pi^+$ Candidate

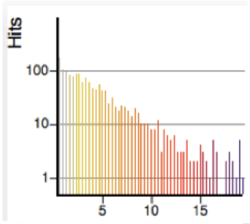


$\nu_\mu\, e^- \rightarrow \nu_\mu\, e^-$ Candidate



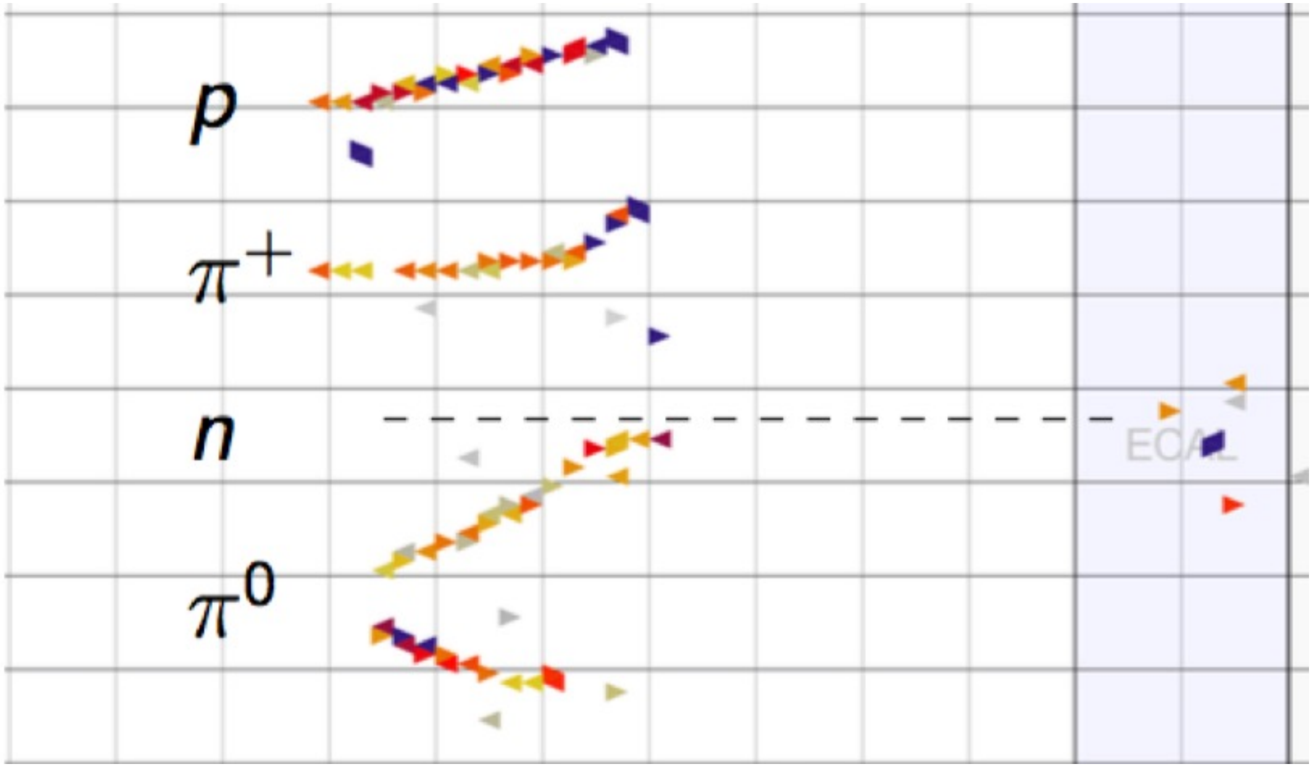


Deep Inelastic Scattering candidate

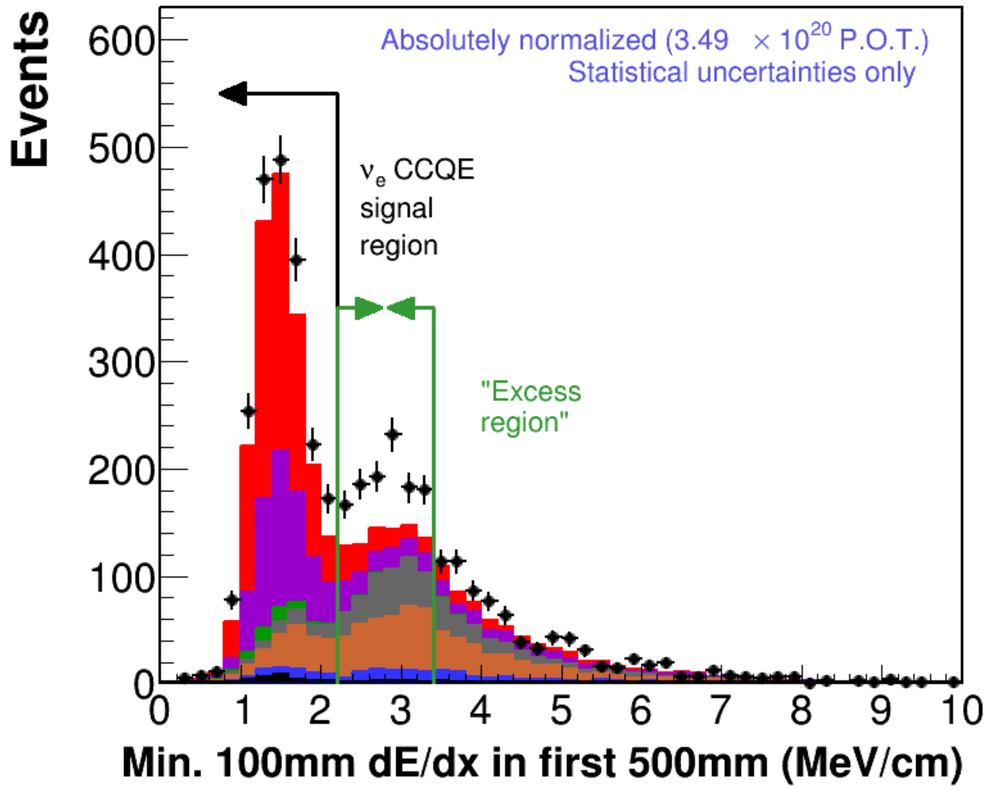


Particle Identification in Scintillator

- Limited by how much light you collect
- How finely segmented the detector is



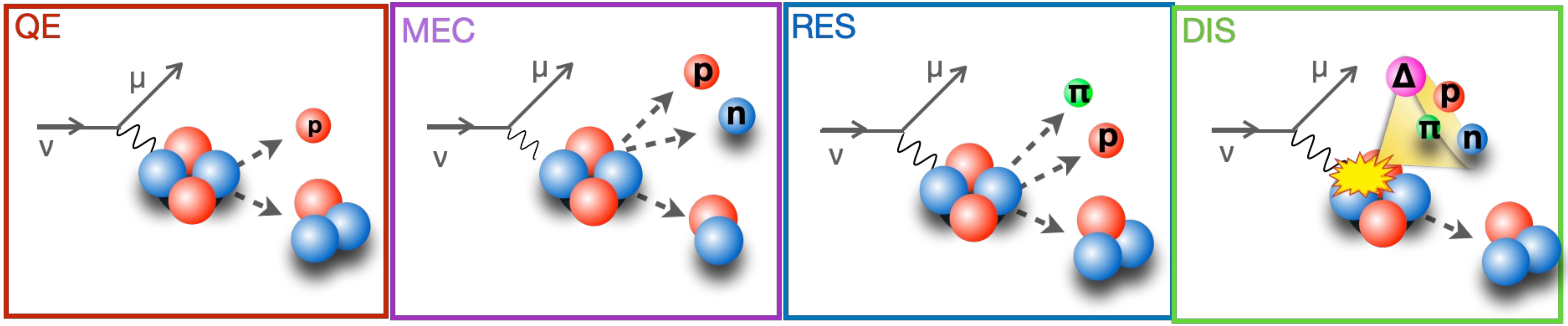
Example from MINERvA:
Triangles 3.3cm wide, 1.7cm tall



Phys. Rev. Lett. 117, 111801 (2016)

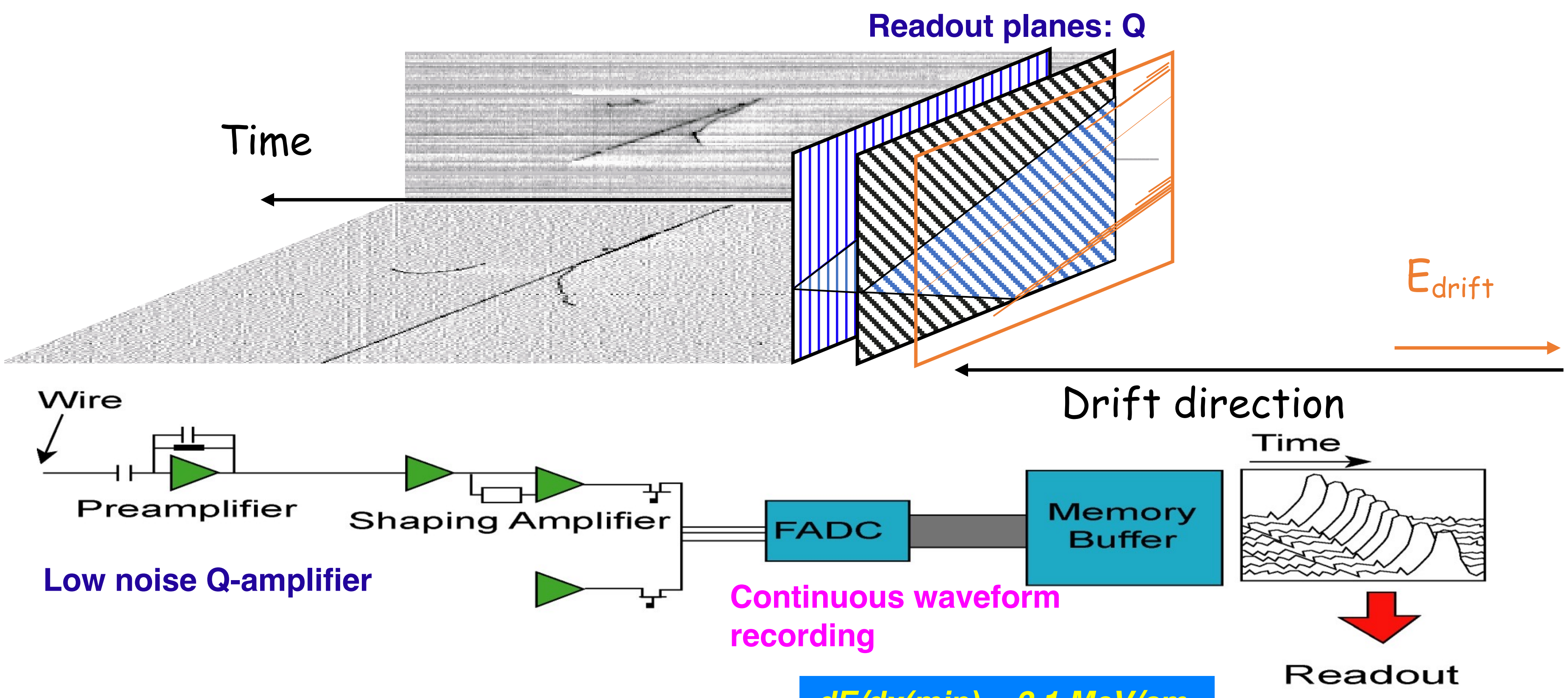
Neutrino Energy Reconstruction

- Homework #4:
  - Given the quasi-elastic hypothesis, derive an equation for the initial state neutrino energy given all the information you have from a scintillator detector
- Question: what happens for other final states? What is the energy a scintillator detector can measure?



Liquid Argon TPC

Liquid Argon Time Projection Chamber

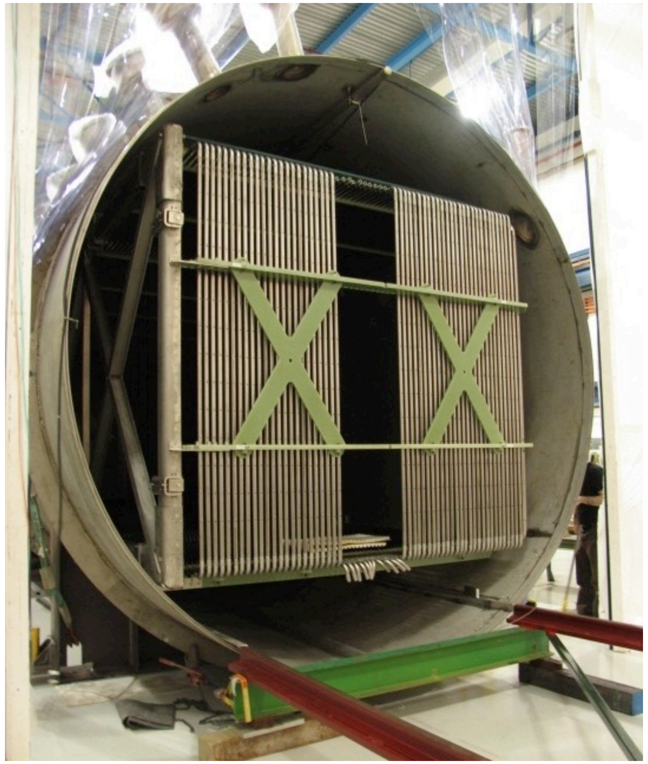


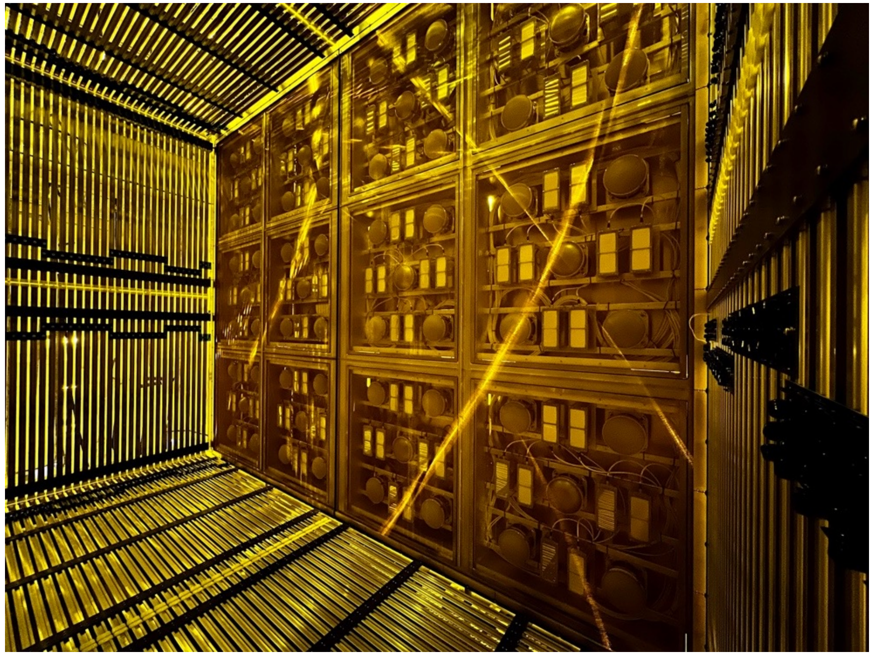
- Ingredients
  - Very pure argon
  - Strong electric field
  - Several planes of wires

dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
Density: 1.4 g/cm3
Xo=14cm
lINT =83cm

ICARUS/MicroBooNE/SBND

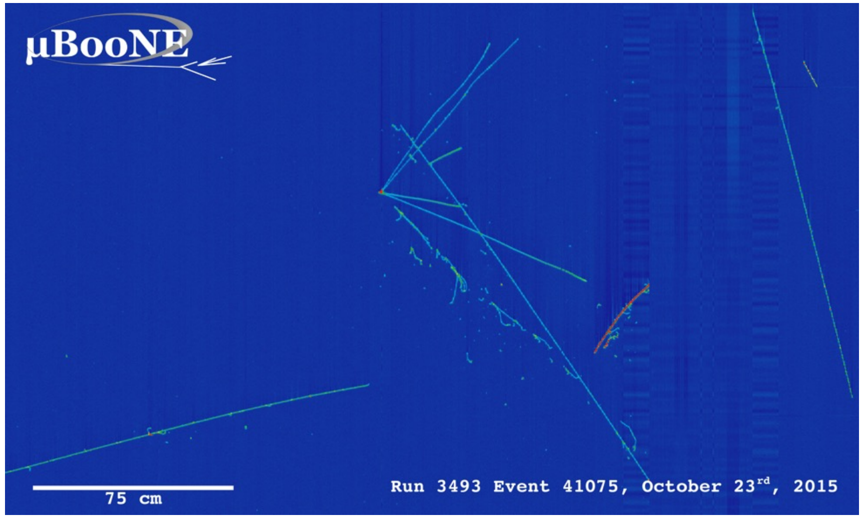
- Active mass: 476 tons / 87 tons/ 112 tons
- Wire spacing: 3mm (all)
- Electron drift distance: 1.5m/2.5m/1.5m
- 74/ 30 / 60 PMT's for scintillation light from pure Argon (timing)
- ICARUS: <E_ν> ~ 20GeV, L=730km
  - Took data in CNGS beamline, installed in MiniBooNE beamline
- MicroBooNE: <E_ν>~0.8GeV, L=1km
  - Taking in MiniBooNE beamline (BNB)
- SBND: : <E_ν>~0.8GeV, L=0.11km
  - Taking in MiniBooNE beamline (BNB)



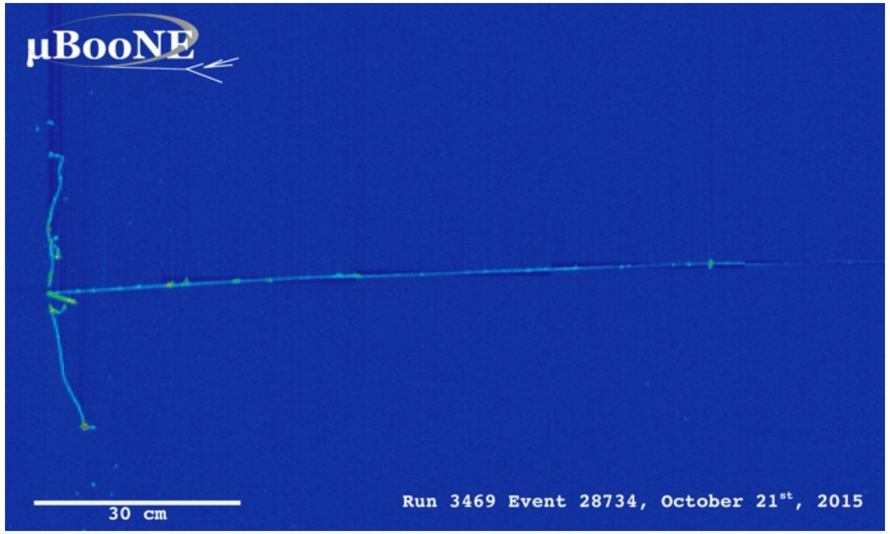


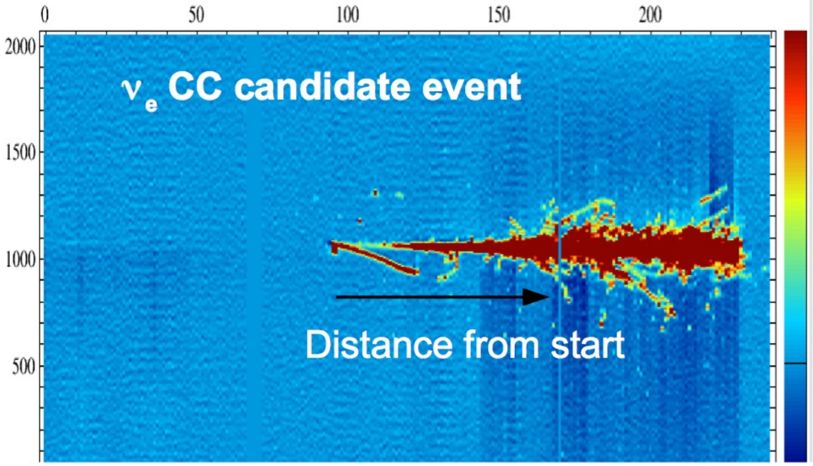
Examples of Liquid Argon Events

- Lots of information for every event…

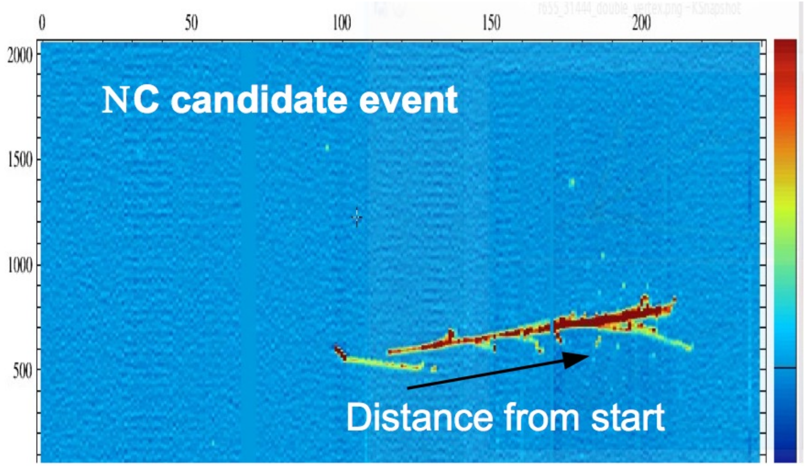


~1GeV beamline events



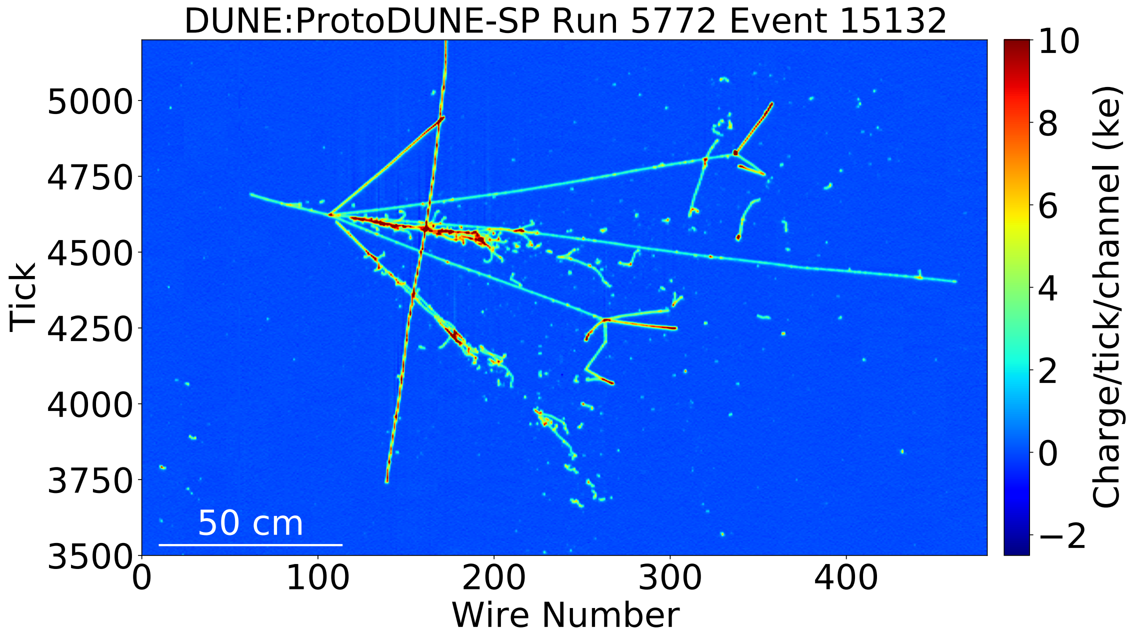


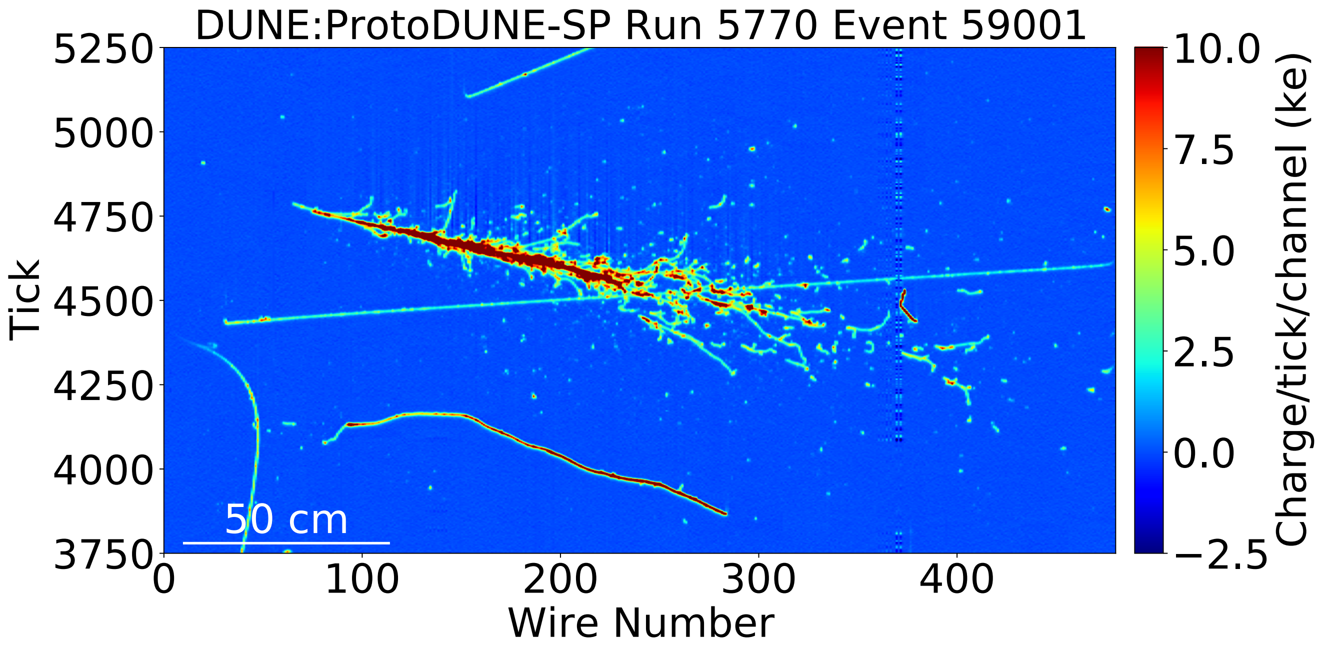
A. Szelc, ν2014, Argoneut in NuMI
B. ~3GeV beamline



Quick test of Particle ID in Liquid Argon:

- Which of these is an electron, and which one is a pion?





- Can you guess the electron energy from the shape alone?

Reference: JINST 15 (2020) P12004

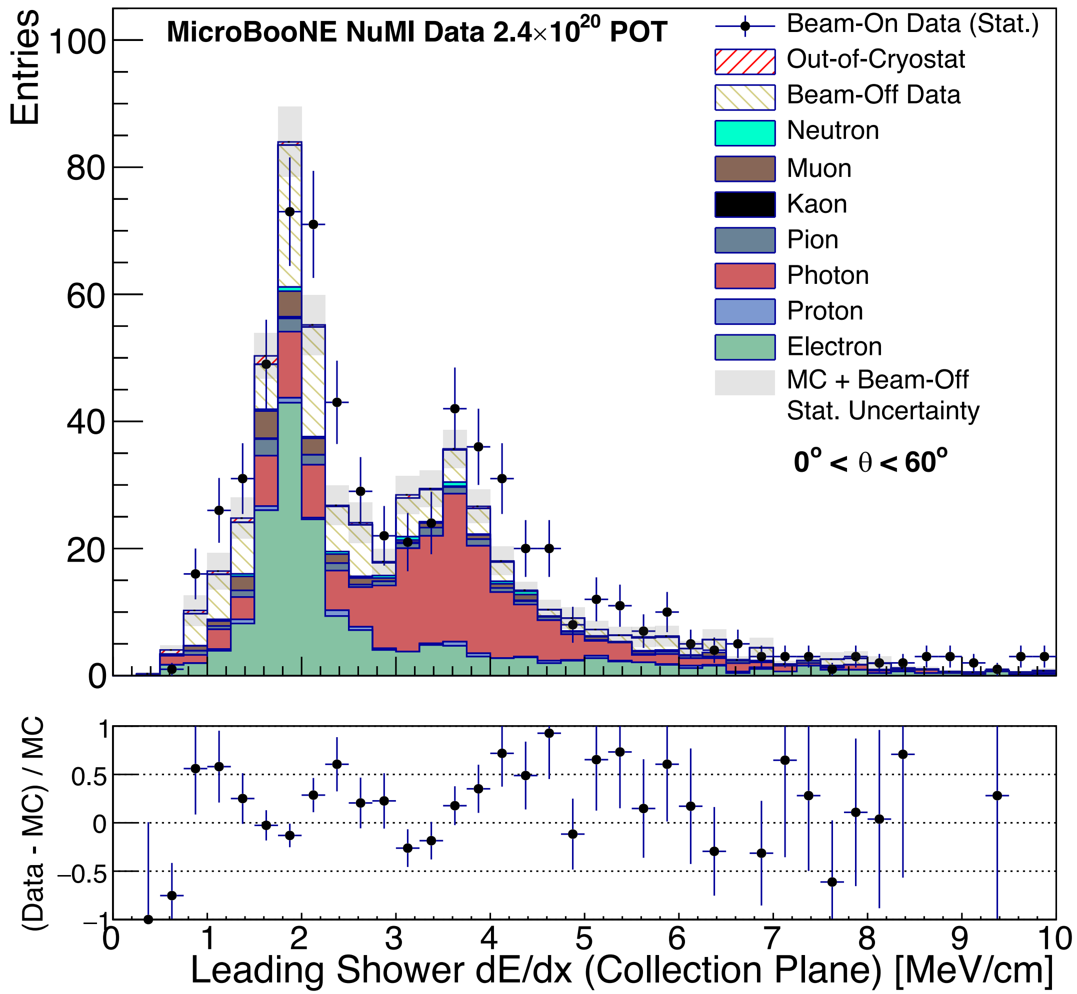
π^0 identification in Liquid Argon

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?

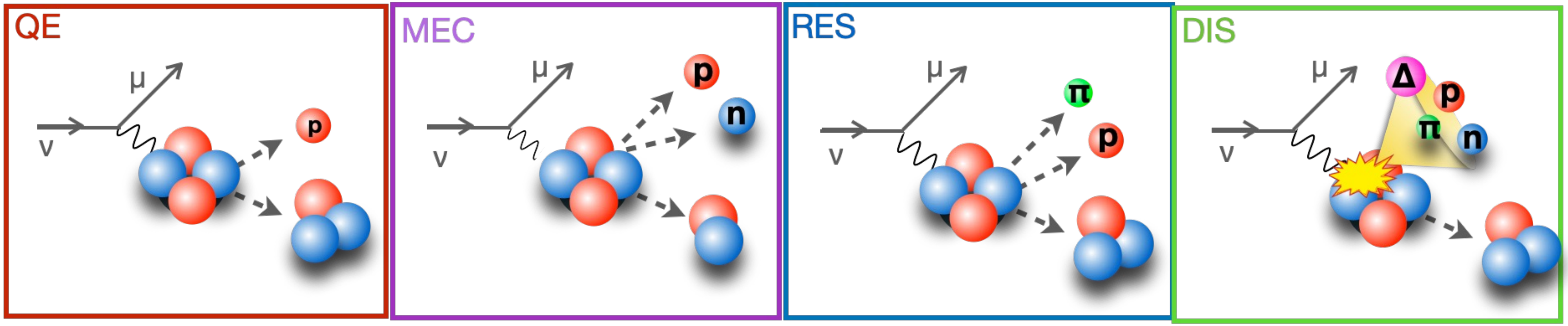
What about the rejection factor for π^0's?



MicroBooNE, Phys. Rev. D 104, 052002 (2021)

Neutrino Energy Reconstruction

- Homework #5:
  - Given the quasi-elastic hypothesis, derive an equation for the initial state neutrino energy given all the information you have from a liquid Argon detector
- Question: what happens for other final states? What is the energy a liquid argon detector can measure?

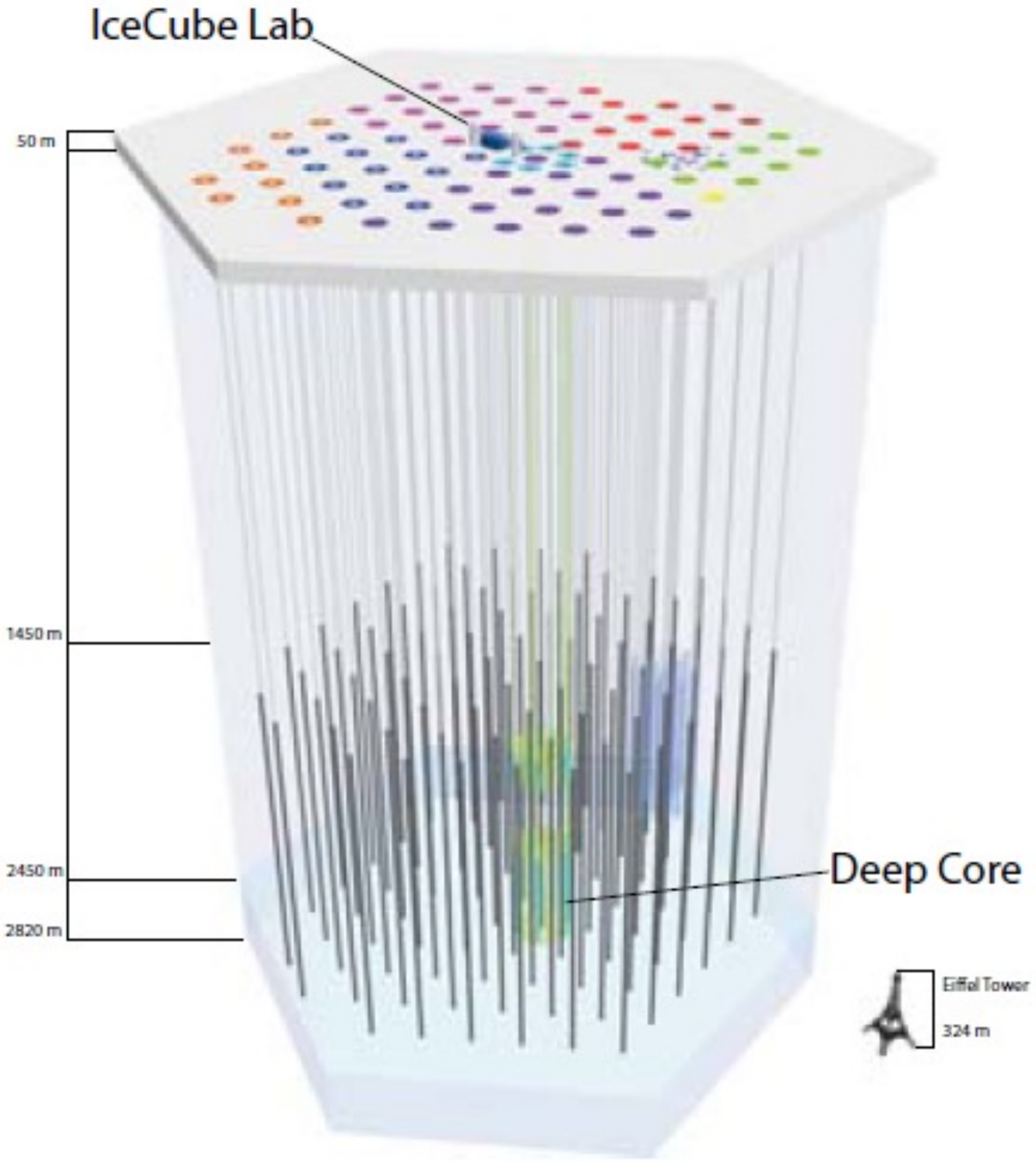


Backup

More information on Neutrino Detectors, more Detectors

Ice as Detector Medium

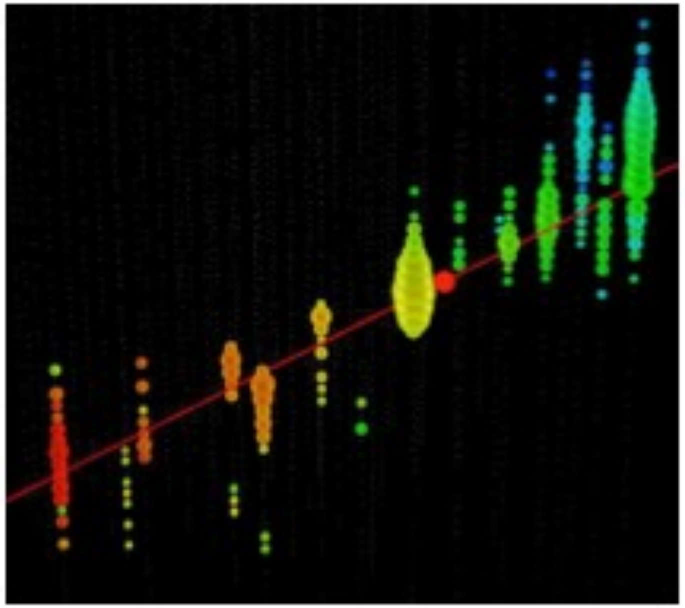
- ICECUBE:
  - 1km^3 volume
  - 86 strings, 5160 PMTs
  - Need to be deep below surface where ice is clear
  - 17m spacing between 2 PMT's on one string
  - Smaller PMT spacing would mean lower energy thresholds

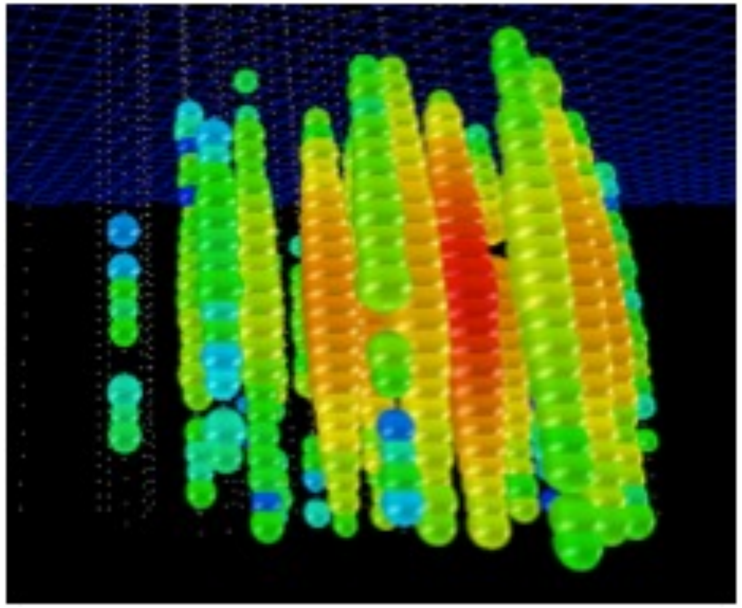


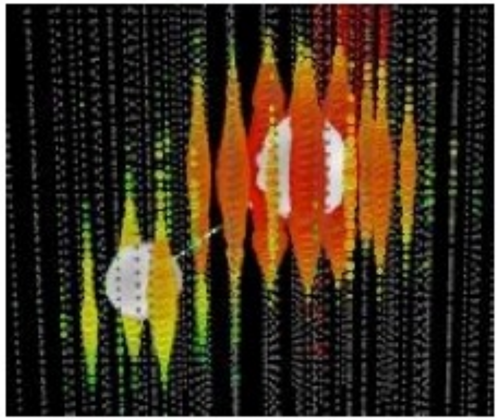
Whitehorn, DPF 2013

Event Signatures in Ice

- Muon Neutrino (data)
  - <1^o angular resolution
  - Factor of 2 muon energy resolution
- Neutral Current or ν_e (data)
  - 10^o angular resolution (high energy)
  - 15% deposited energy resolution
- ν_τ (simulation)

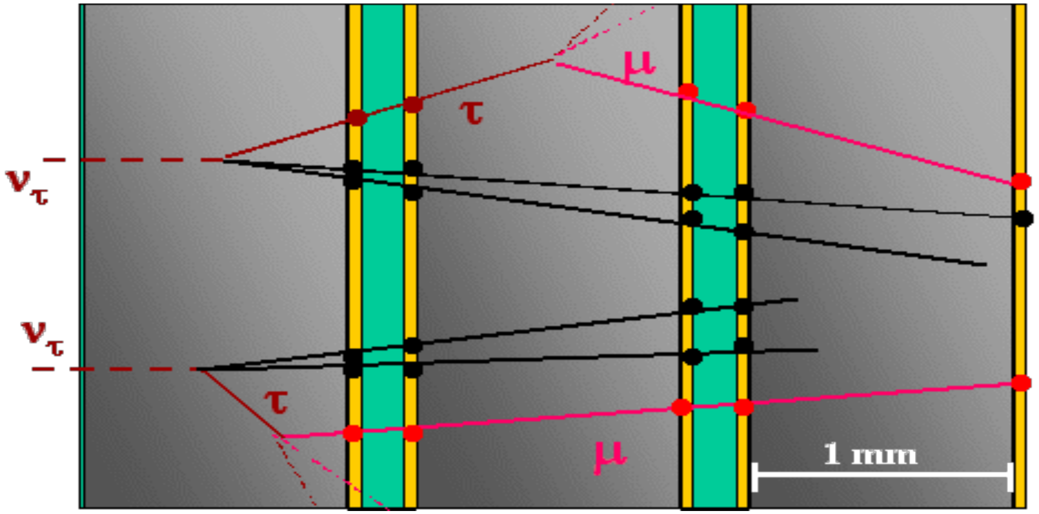


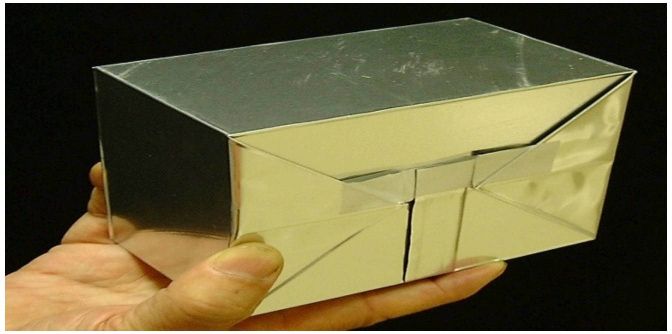




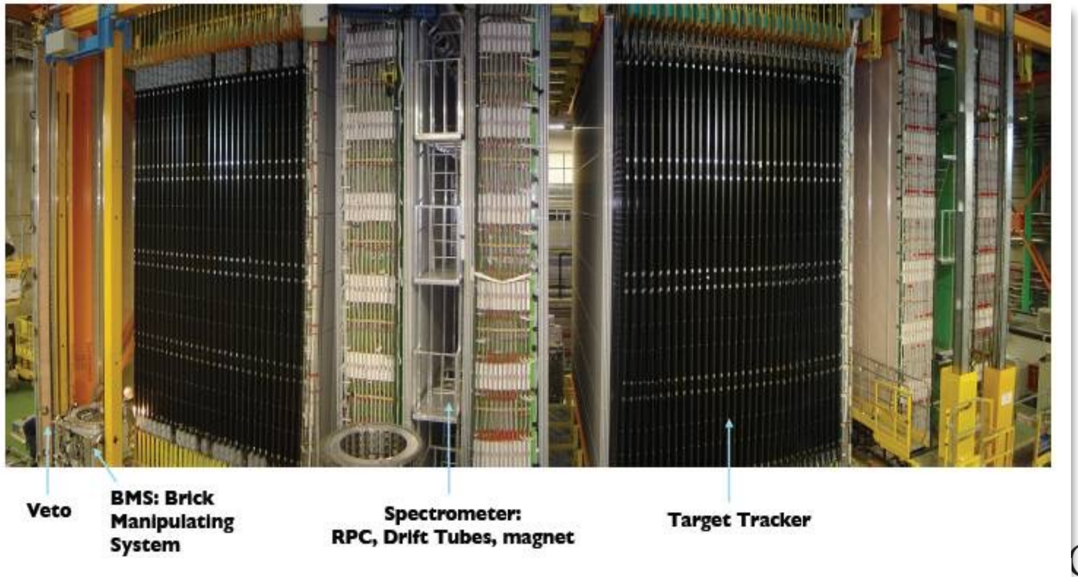
Whitehorn, DPF 2013

Lead-Emulsion Detector (OPERA)



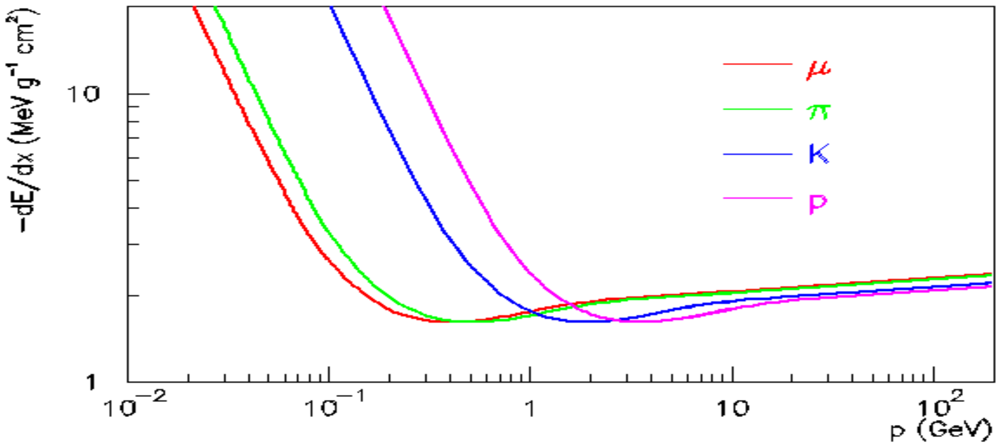


- 1.2kT emulsion detector
  - 146621 bricks, each 8.3kg
  - 56 (1mm) Pb sheets
  - 57 (300mm) FUJI emulsion layers
  - 2 (300mm) changeable sheets (CS)



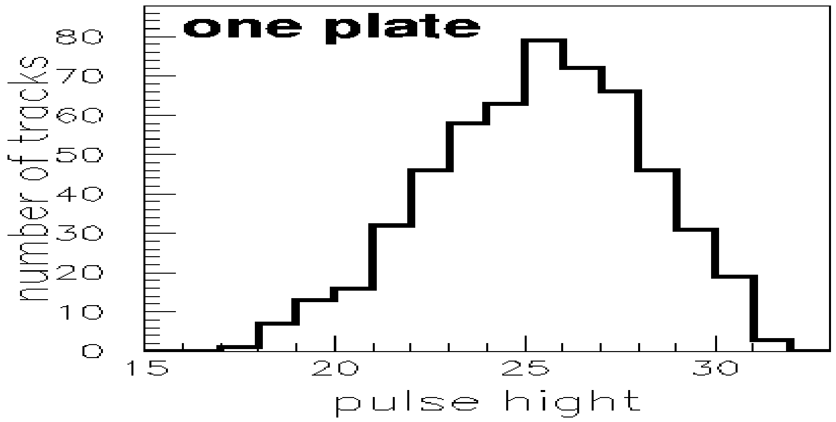
Particle ID in Emulsion

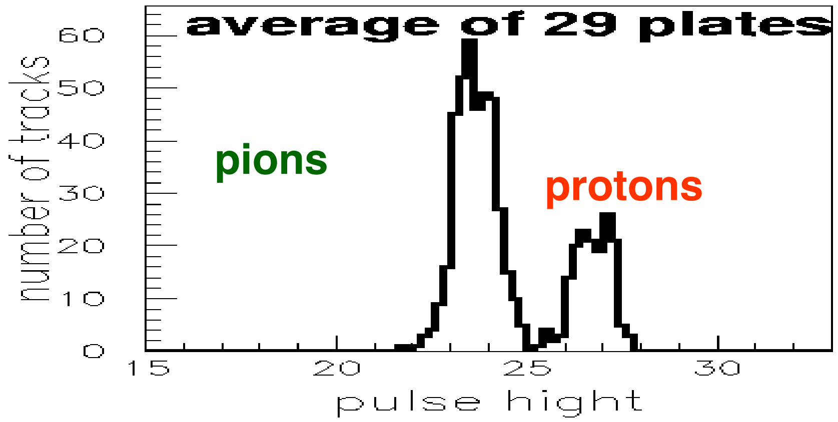
Grain density in emulsion is proportional to dE/dx



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

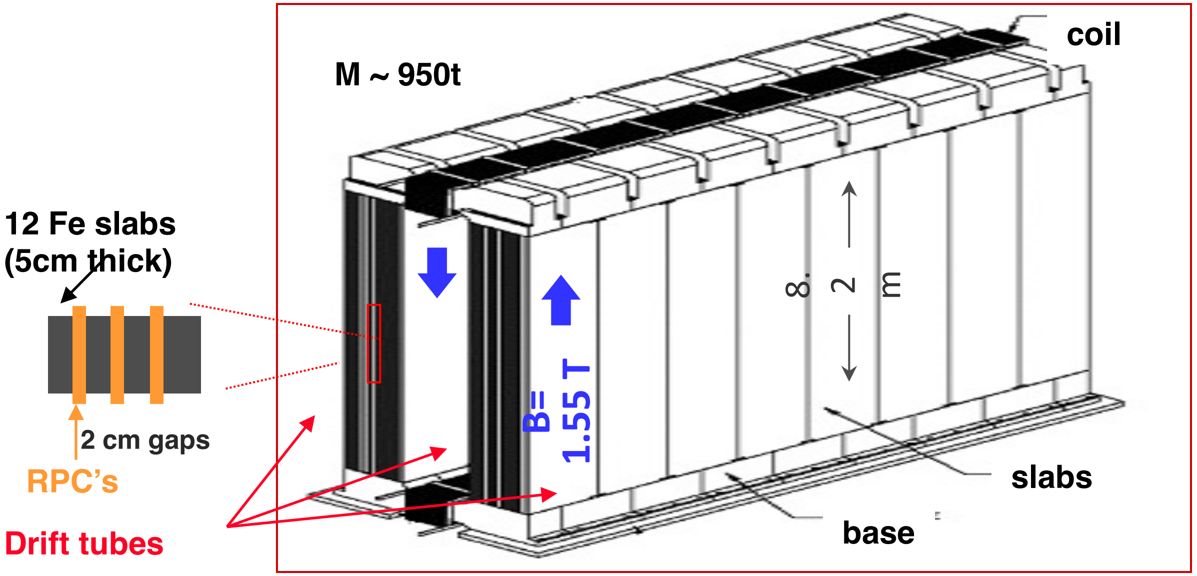
Test exposure (KEK) : 1.2 GeV/c pions and protons, 29 plates





Plots courtesy M. DeSerio

Muon Spectrometer w/RPC



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

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

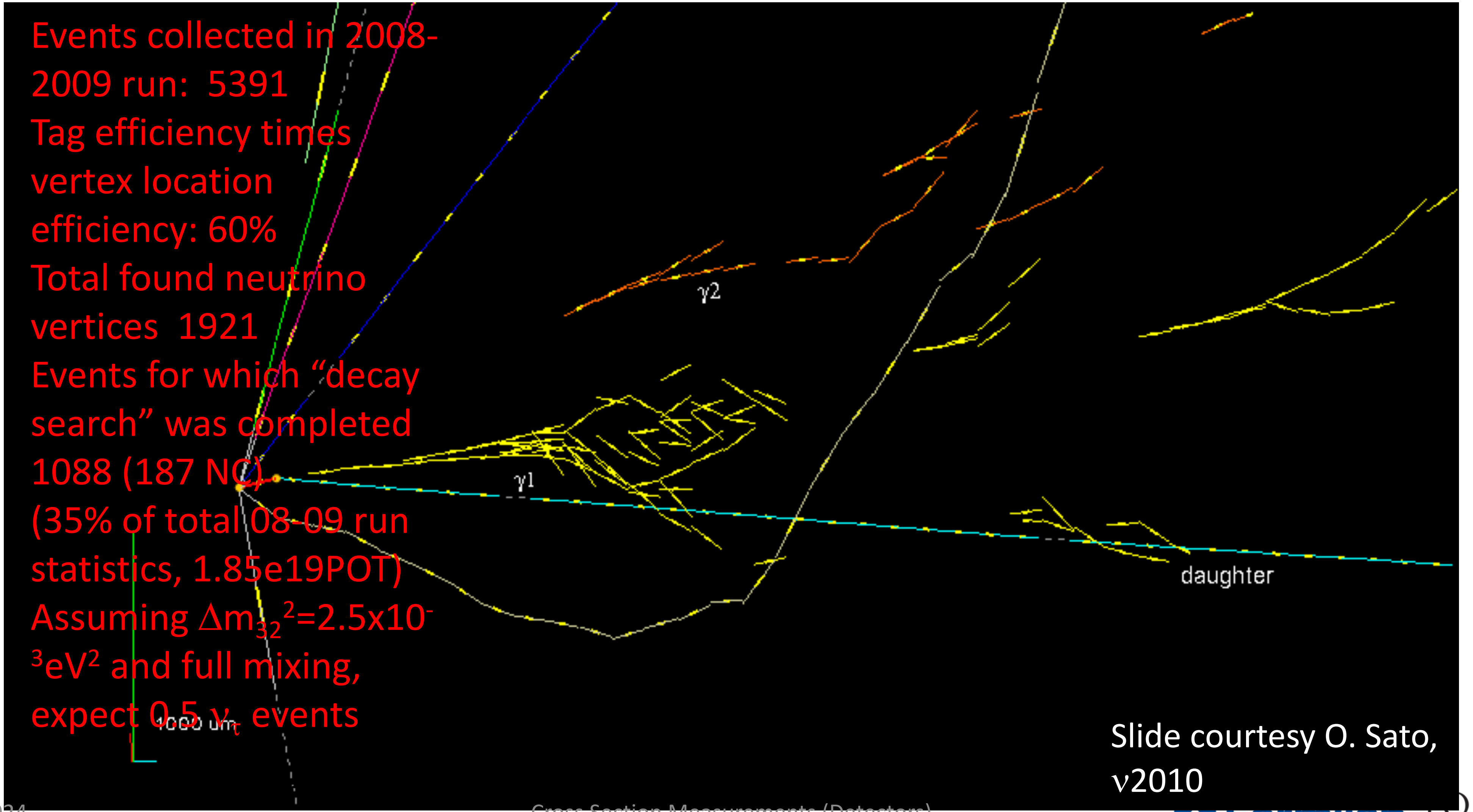
μidentification:
$\mu\varepsilon > 95\%$ (TT)

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

Inner Tracker:
11 planes of RPC's
21 bakelite RPC's (2.9x1.1m^2) / plane
(~1,500m^2 / spectrometer)
pickup strips, pitch:
3.5cm (horizontal), 2.6cm (vertical)

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

First Tau Neutrino Detected



Events collected in 2008-2009 run: 5391

Tag efficiency times vertex location efficiency: 60%

Total found neutrino vertices 1921

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

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

Slide courtesy O. Sato, ν2010