PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 56400
Introduction to Elementary Particle Physics I

Lecture 7

Fall 2019 Semester

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Liquid Scintillator

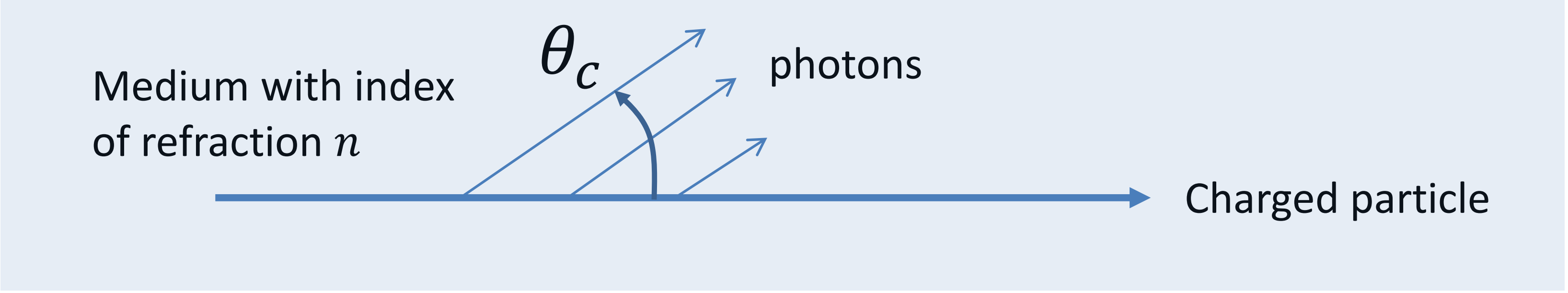
- Scintillating chemicals can be dissolved in, for example, purified mineral oil
- Can be used to fill a very large volume
- Might not be rad-hard
  - Chemical impurities can be created by ionizing radiation that reduce light output or decrease attenuation length
  - You might end up with a very large volume of radioactive waste
  - Disposal might be expensive…

Particle Detectors

- Detecting charged particles using the scintillation process
  - Photon yield is proportional to the ionization energy loss
  - Photons are converted to photo-electrons at the cathode of a photomultiplier tube
  - Photomultiplier tubes amplify the photo-current
  - Alternatively, solid state detectors serve the same purpose
- Charged particles can also emit Cherenkov light

Cherenkov Radiation

- When a charged particle moves through a medium with a speed that is faster than the speed of light in the medium, it emits Cherenkov radiation



$$\cos\theta_c = \frac{1}{n\beta}$$

$$\frac{dN}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Cherenkov Light

- Consider a muon with an energy of 10 GeV moving through water ($n = 1.33$)

$$\beta = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} = \sqrt{1 - m^2/E^2} = 0.99994$$

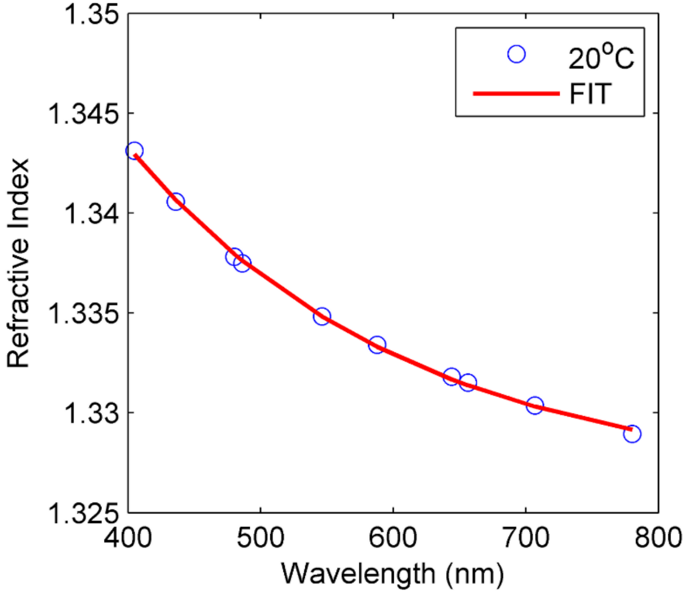
- Angle of Cherenkov light emission:

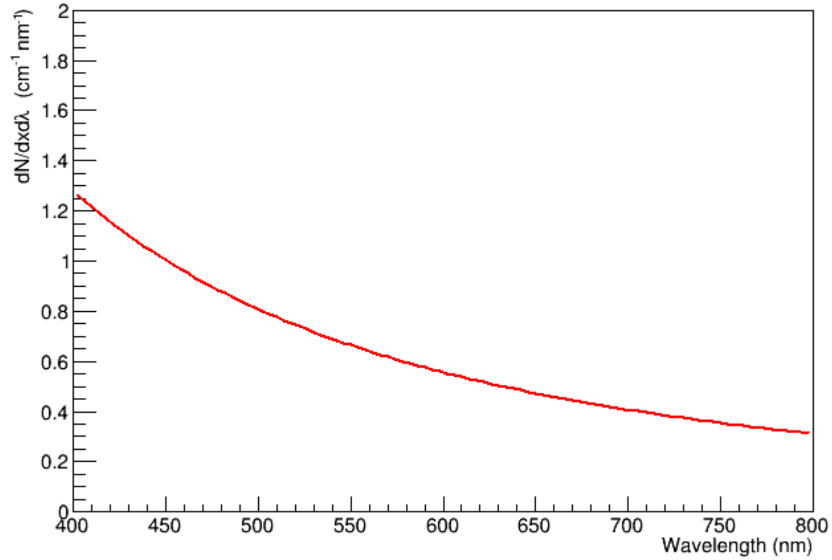
$$\cos\theta_c = \frac{1}{n\beta} = \frac{1}{1.33} = 0.75$$

$$\theta_c = 41.4^\circ$$

- Cherenkov light is emitted immediately
  - Scintillation light is slower and can have long components
- How many photons are produced?

Cherenkov Light





Light yield integrated over 400-800 nm:

$$\frac{dN}{dx} = 252 \text{ cm}^{-1}$$

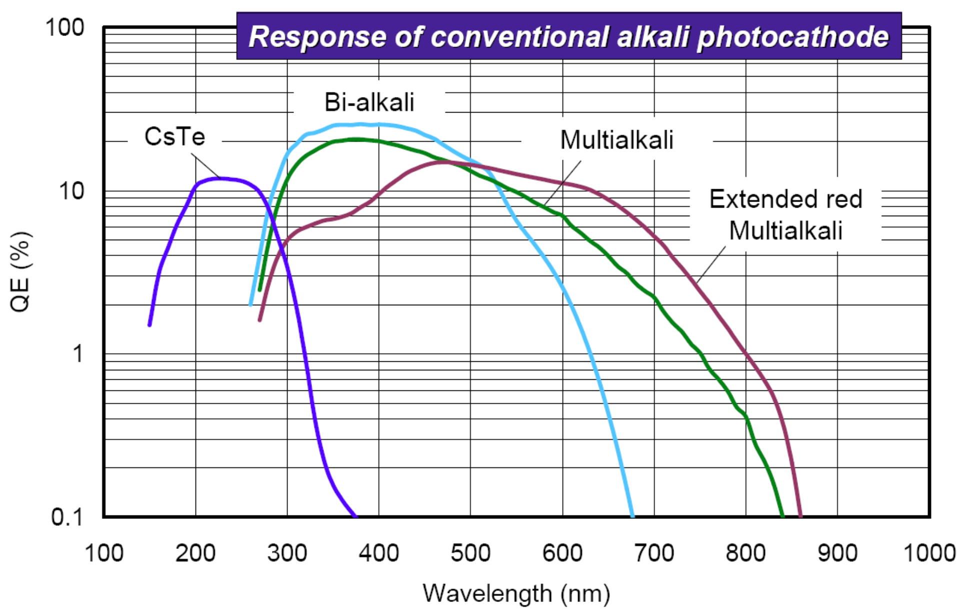
If the muon travels through 10 meters of water, then

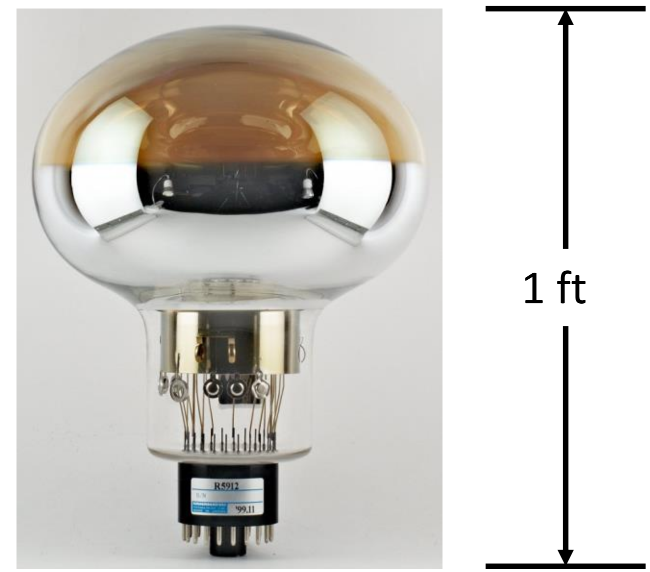
$$N = 252{,}000$$

Much less light per unit length than for scintillator.

Cherenkov Light

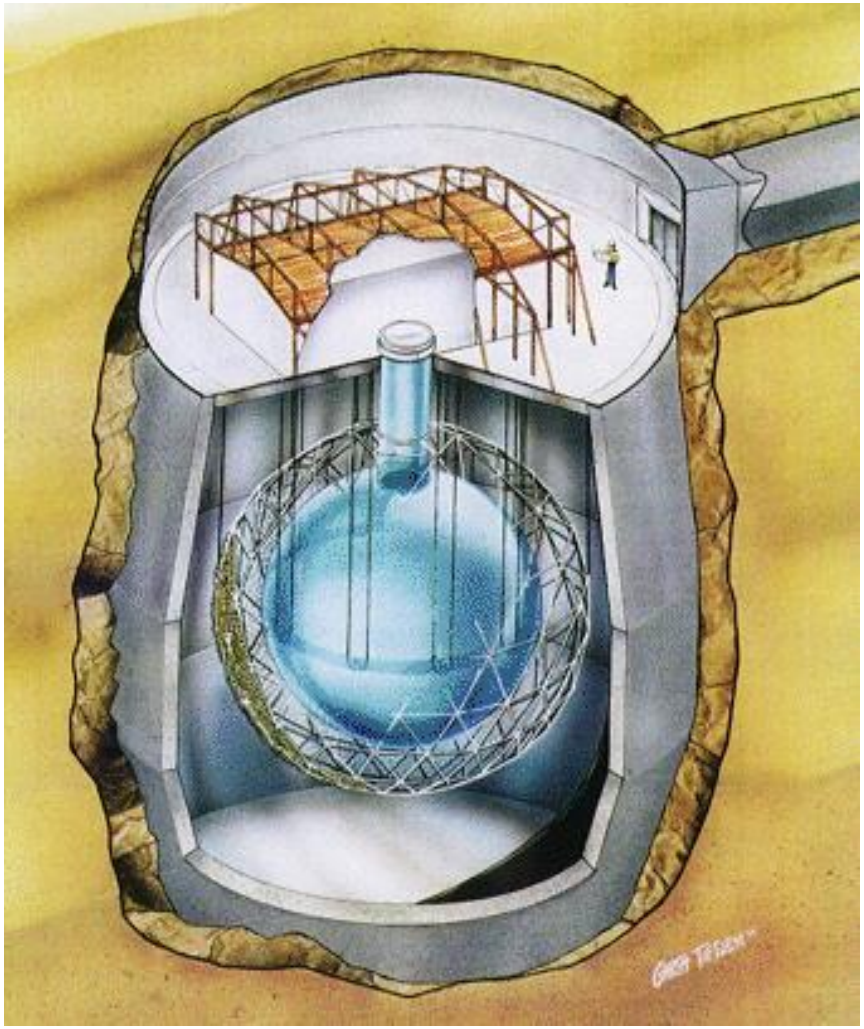
- Spectral response of photomultiplier tubes:

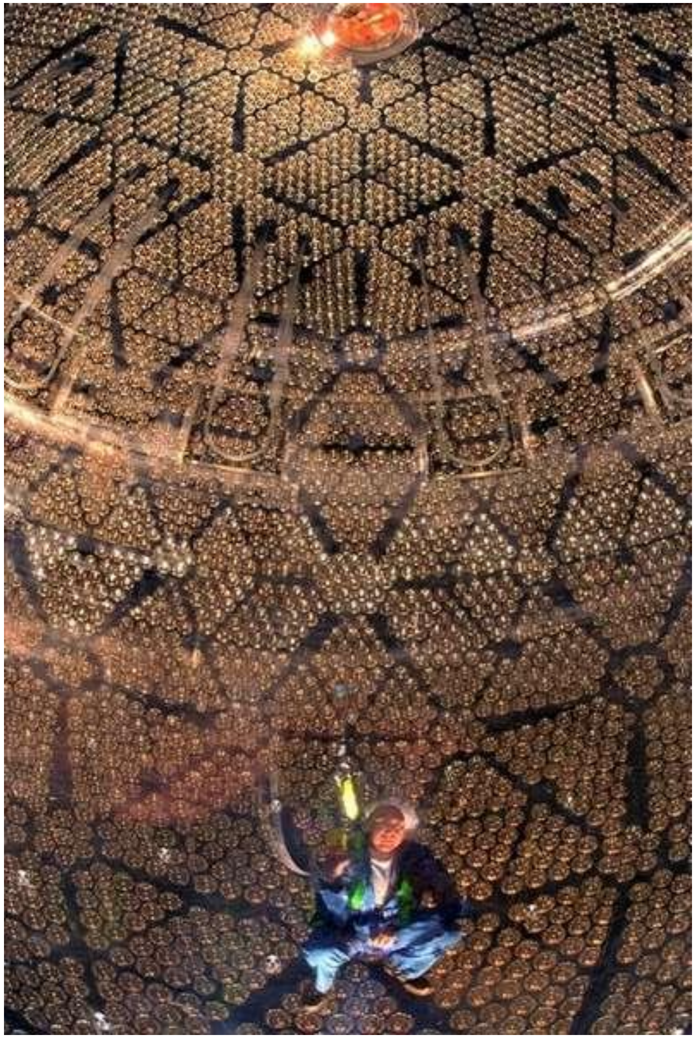




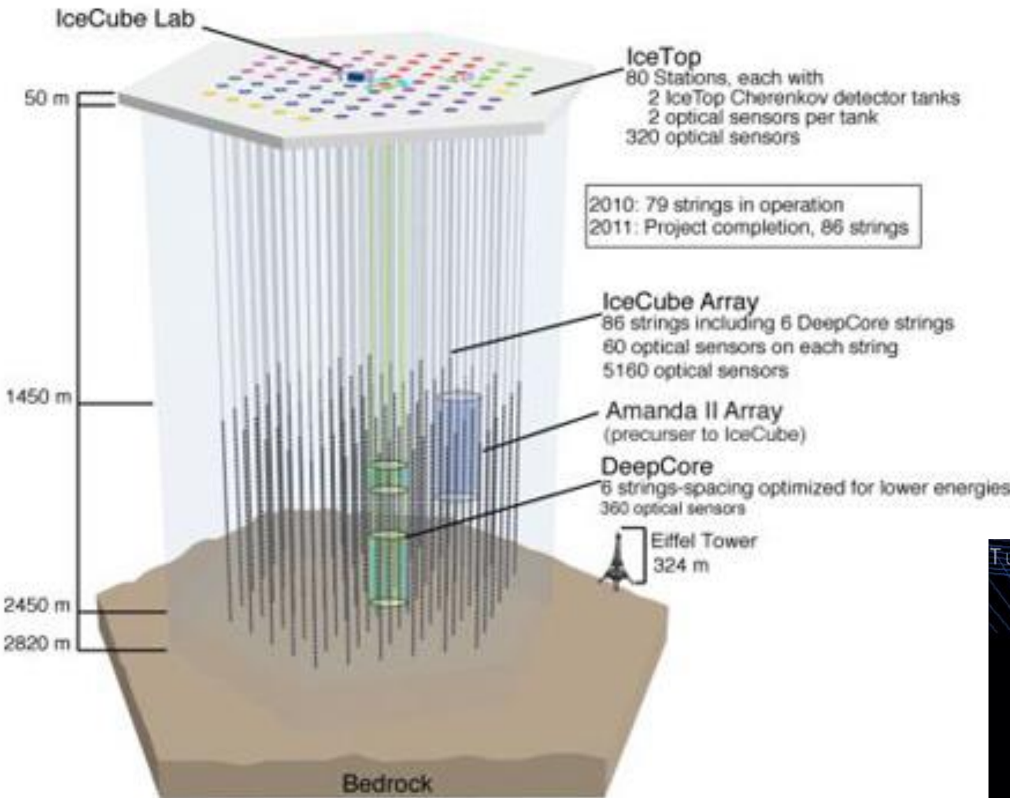
- Average quantum efficiency is about 5-10%
- Light collection efficiency might be 20%
- Number of photoelectrons: 2500 – 5000.

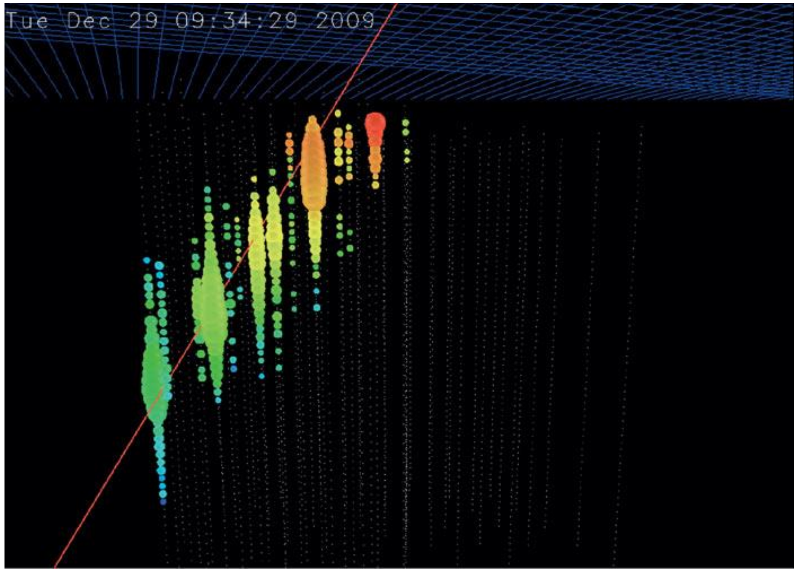
Water Cherenkov Detectors





Large Cherenkov Detectors





Color indicates time (red is early, green is late)
Size indicates light yield

Threshold Cherenkov Counters

- If $\beta < 1/n$ then no light is emitted.
- Thin volumes of gas with $n \approx 1$ can be used to distinguish between pions ($m = 139.5\ \mathrm{MeV}$) and kaons ($m = 493.7\ \mathrm{MeV}$)
- Suppose a magnet selects charged particles with momentum $p < 2\ \mathrm{GeV}$.

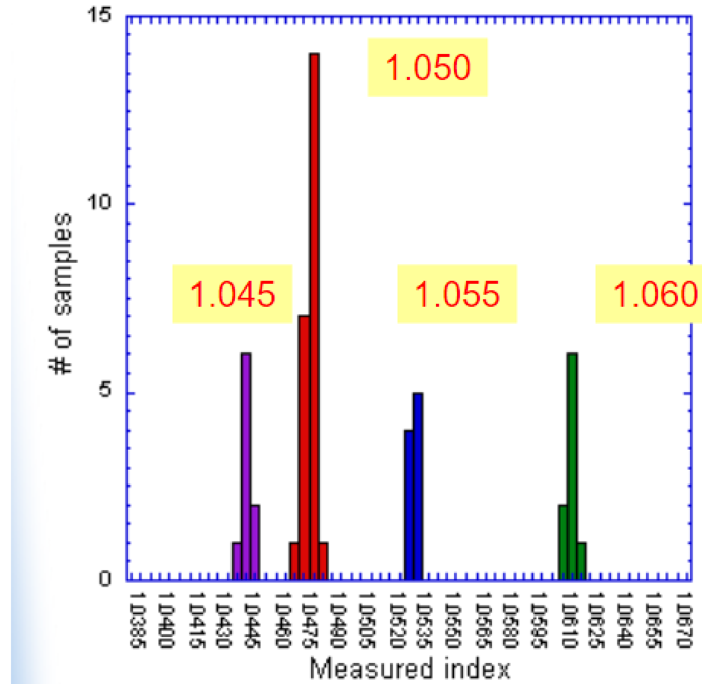
$$\beta_\pi = 1/\sqrt{1 + m_\pi^2/p^2} < 0.9976$$

$$\beta_K = 1/\sqrt{1 + m_K^2/p^2} < 0.9709$$

- We need a material with $n \approx 1.05$ so that pions will emit Cherenkov light but kaons won't.

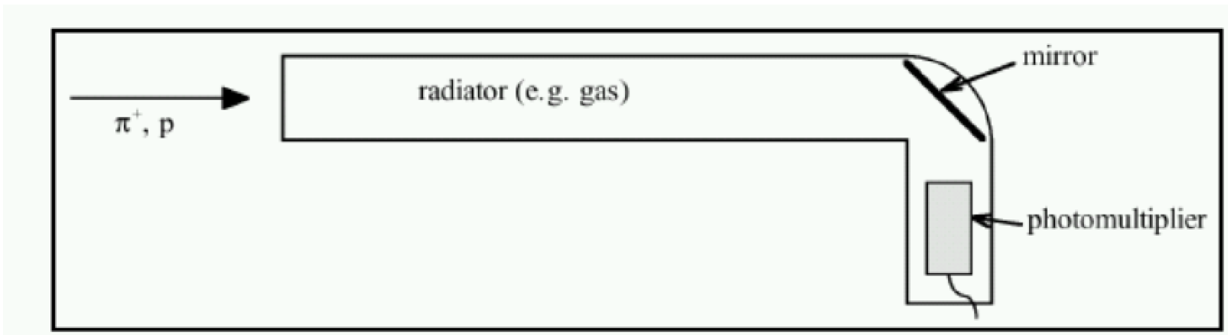
Threshold Cherenkov Counters

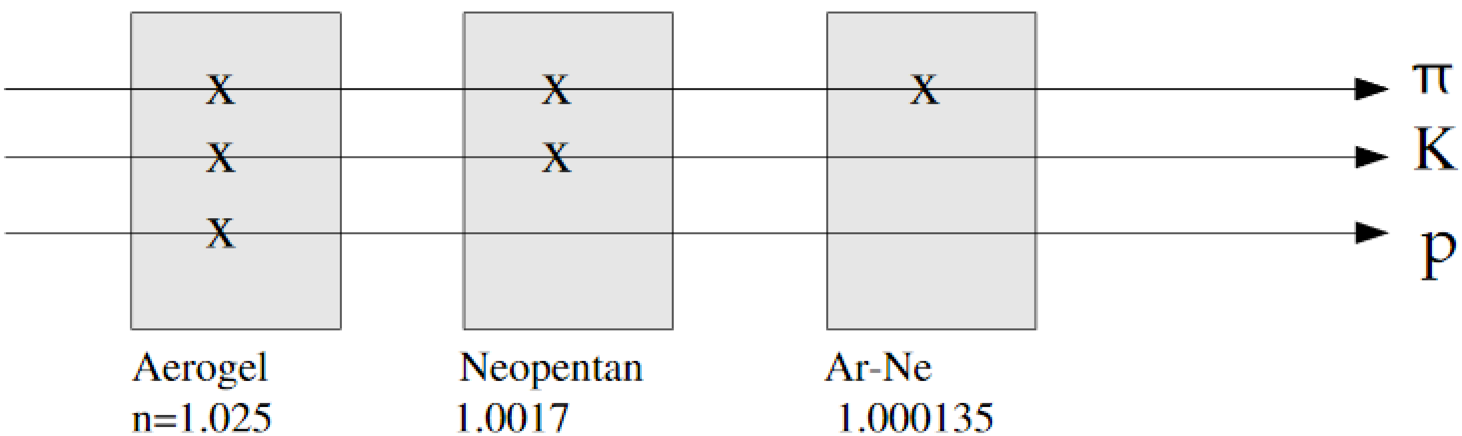
- Such materials do exist and they are transparent



- See, for example: https://www.youtube.com/watch?v=SWnqOc-cWpU

Threshold Cherenkov Counters

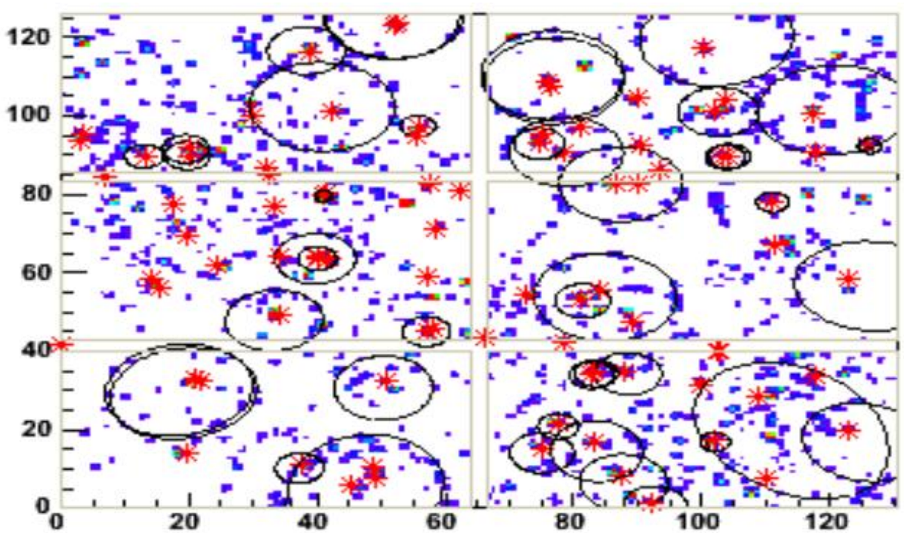


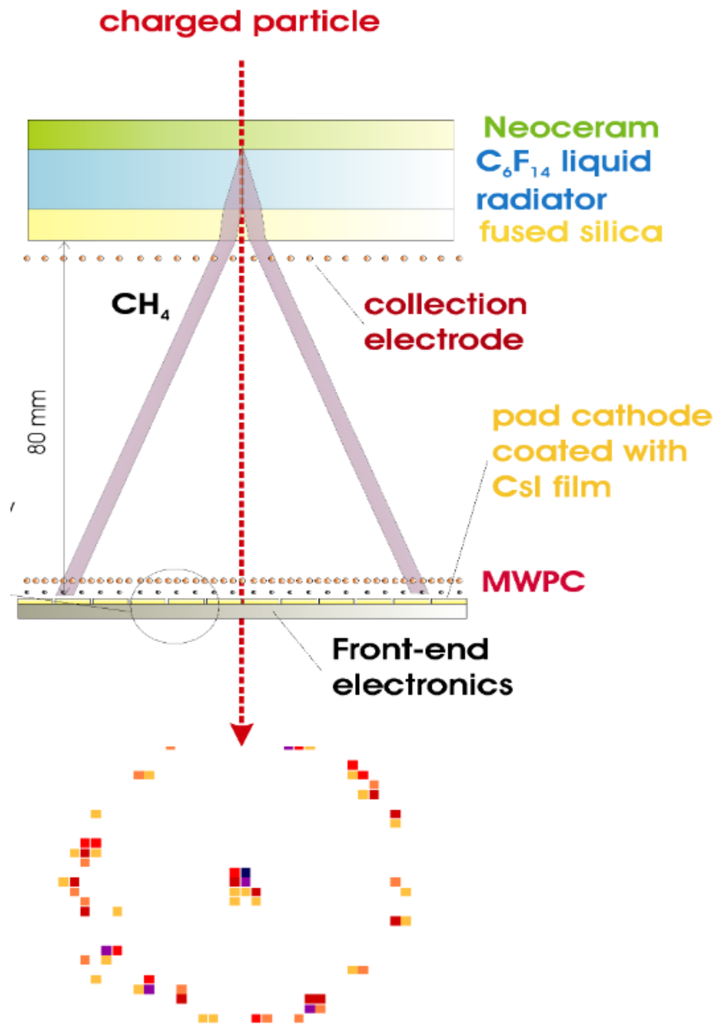


Ring Imaging Cherenkov Detectors

The radius of the ring determines the angle of light emission, θ_c which gives the velocity:

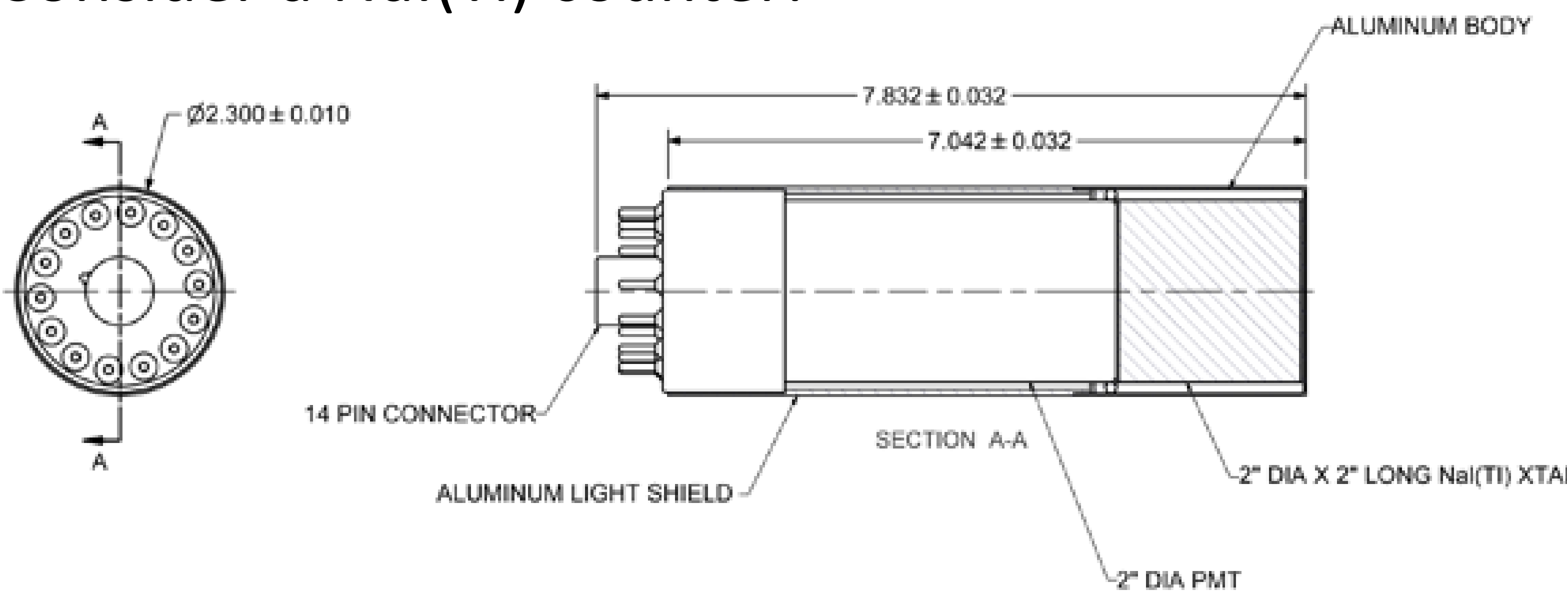
$$\beta = \frac{1}{n \cos \theta_c}$$





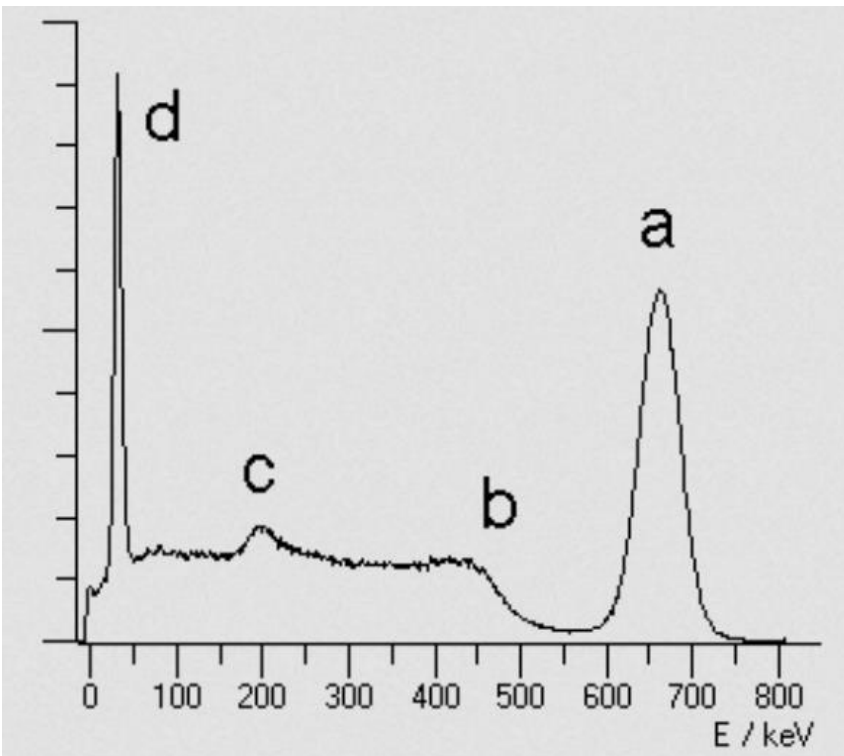
Detection of Photons

- After Compton scattering, we can detect the ionization of the scattered electron
- If the photon is above threshold, we can detect both the electron and positron after pair production
- Consider a NaI(Tl) counter:



Gamma Ray Spectrum

Cs-137 spectrum: $E_\gamma = 662\ \mathrm{keV}$



a) All of the photon's energy is absorbed within the crystal.
b) Compton edge: photon scatters out of the crystal.
c) Backscatter peak.

Gamma Ray Spectrum

- Photon energy:

$$\frac{1}{E'} - \frac{1}{E} = \frac{1 - \cos\theta}{m_e}$$

- Electron energy:

$$\frac{\Delta E}{E} = \frac{E - E'}{E} = 1 - \frac{1}{1 + E/m_e(1 - \cos\theta)}$$

- When the photon back-scatters at $\theta = \pi$,

$$\frac{\Delta E}{E} = 0.7215$$

- The Compton edge is located at $E_c = 478\ \mathrm{keV}$

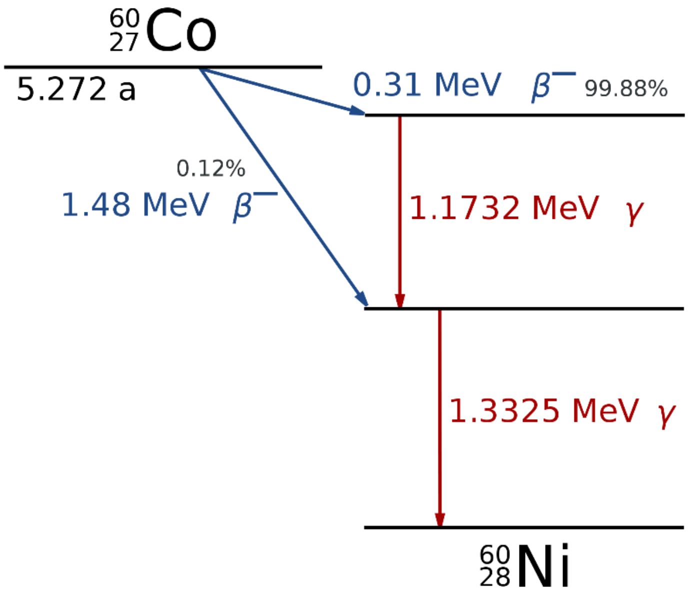
Gamma Ray Spectrum

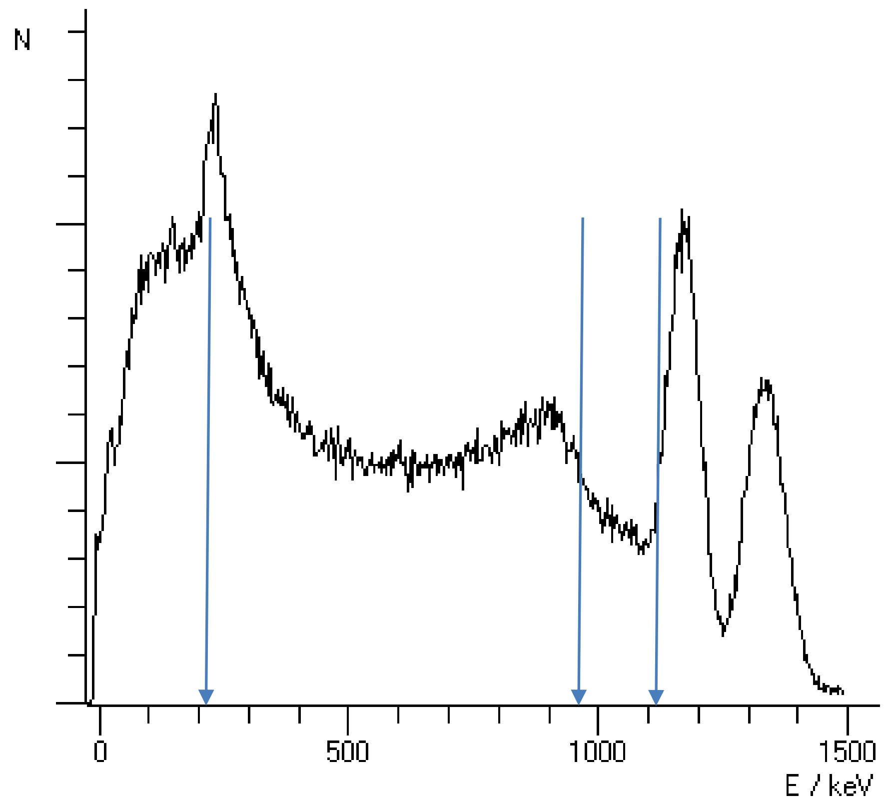
- The backscatter peak results from the gamma ray scattering off of passive detector material back into the crystal, where all its energy is deposited.

$$E' = \frac{m_e}{(1 - \cos\theta) + m_e/E}$$

- When $\theta = \pi, E' = 184.4 \text{ keV}$
- In the limit as $E \gg m_e, E' \to m_e/2$

Other Gamma Ray Spectra





Compton edges are at

$$E_1 = 963 \text{ keV}$$

$$E_2 = 1118 \text{ keV}$$

Backscatter peak is at

$$E_b = 210 \text{ keV}$$

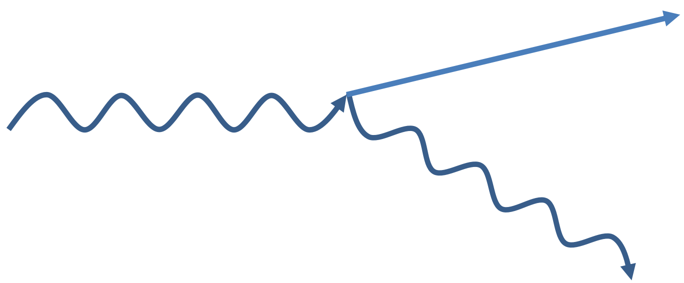
Electromagnetic Calorimeters

- If we want to measure the energy of a high energy photon, we need it to Compton scatter or pair produce
- We also need to contain all the scattered particles within the detector and measure their energy.
- A simple model for electron/photon interactions with matter is the “electromagnetic shower”.
- The mean free path of a high energy electron or photon in material is about one radiation length.
  - Example: For lead,

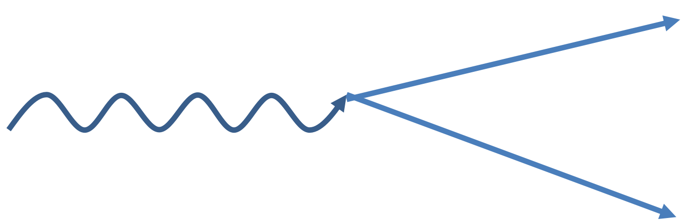
$$\frac{X_0}{\rho} = \frac{6.37\ \mathrm{g \cdot cm^{-2}}}{11.350\ \mathrm{g \cdot cm^{-3}}} = 0.56\ \mathrm{cm}$$

Electromagnetic Showers

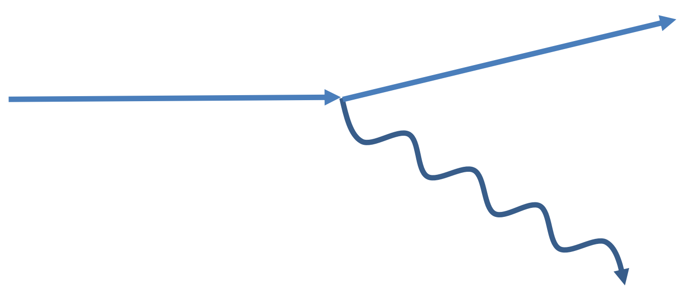
- Electromagnetic splitting processes:



Compton scattering



Pair production



Bremsstrahlung

Electromagnetic Showers

- Sequential branchings can be modeled as a stochastic process:
    1. Propagate particle a distance x with probability distribution
    $$p(x) = \frac{1}{X_0} e^{-x/X_0}$$
    2. Split into two new particles with energy fraction y distributed according to some probability distribution
    $$f(y) = 1 \ \text{(uniform distribution)}$$
    One particle has energy $E \cdot y$ and the other has energy $E \cdot (1 - y)$
    3. Repeat until the energy of a particle falls below the critical energy cutoff, E_c, which is (roughly) the energy at which $E < X_0 \cdot \left(\frac{dE}{dx}\right)_{min}$
- These are essentially the main ideas behind Monte Carlo calculations like GEANT and EGS.

Critical Energy

- The critical energy depends on the material but can be parameterized as a function of Z:

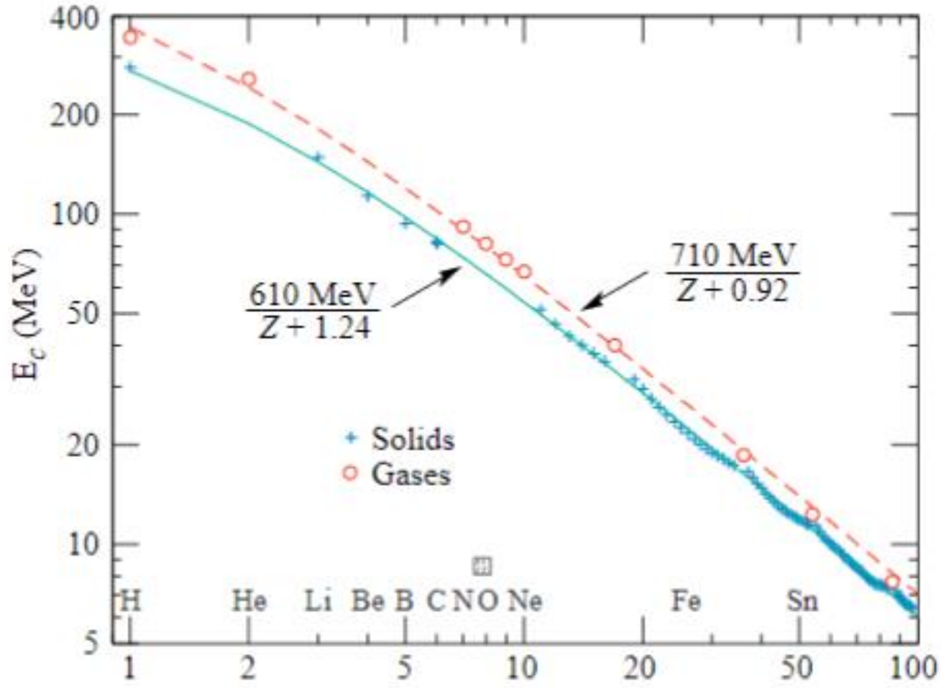
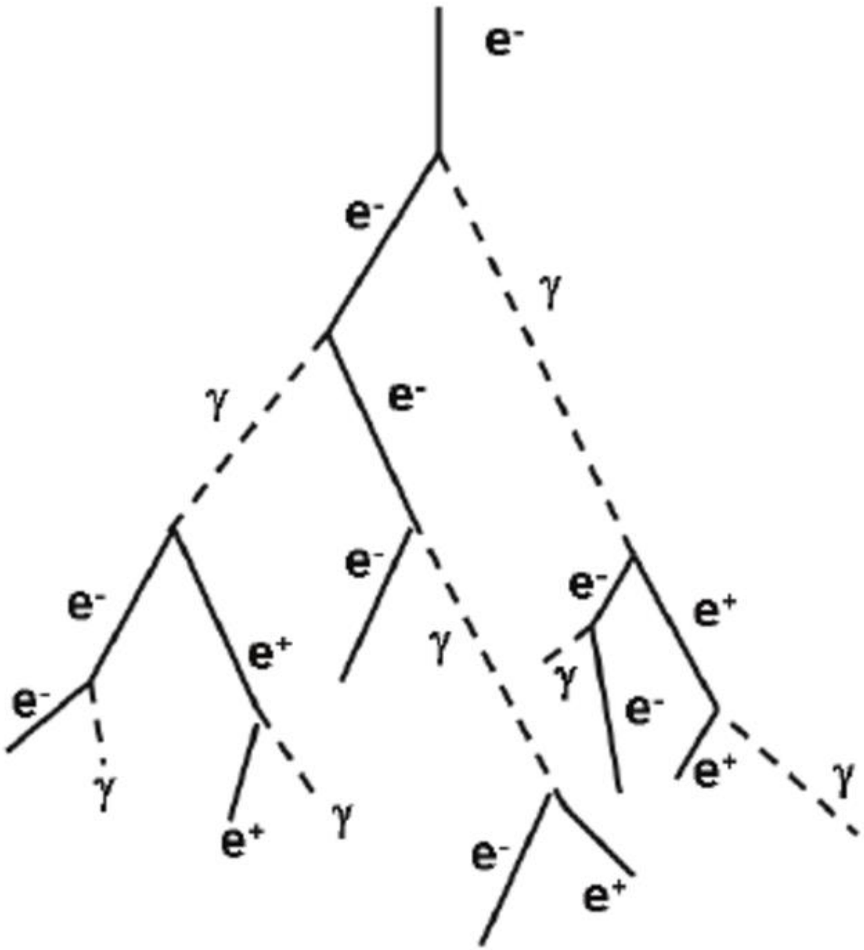
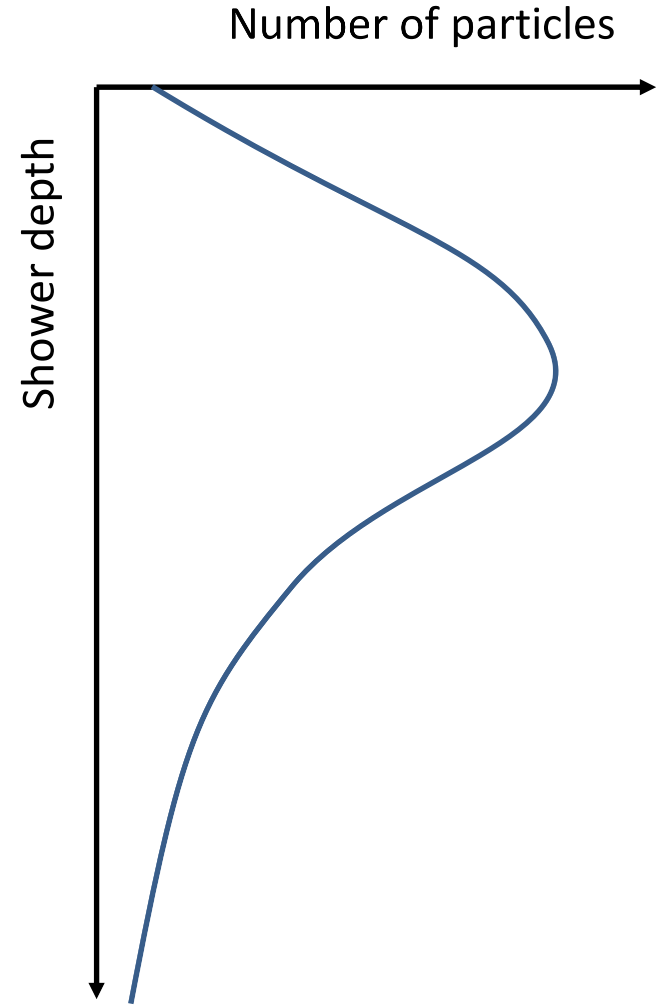


Figure 33.14: Electron critical energy for the chemical elements, using Rossi's definition [2]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

Electromagnetic Showers





Electromagnetic Showers

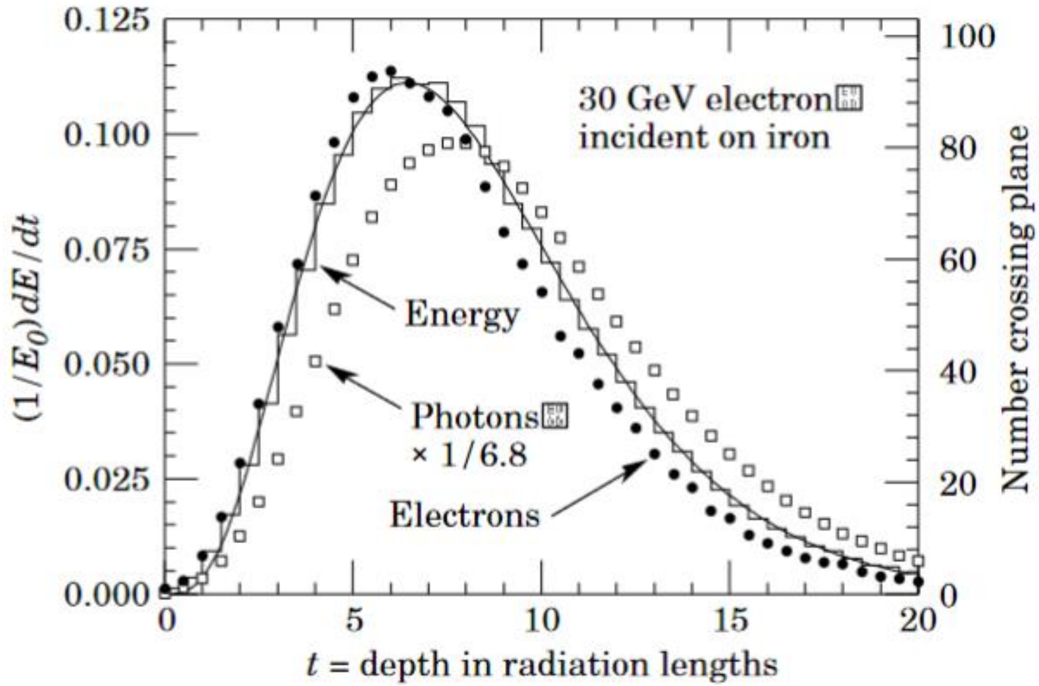


Figure 33.20: An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at $X_0/2$ intervals (scale on right) and the squares the number of photons with $E \geq 1.5$ MeV crossing the planes (scaled down to have same area as the electron distribution).

Electromagnetic Showers

- The longitudinal profile of an electromagnetic shower can be described empirically by a gamma distribution:

$$\frac{dE}{dt} = E_0 b \ \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- The maximum occurs at

$$t_{max} = \frac{a-1}{b} = \log \frac{E}{E_c} \pm 0.5$$

  for electrons (-) and photons (+).

- The transverse size of the shower scales with the Moliere radius,

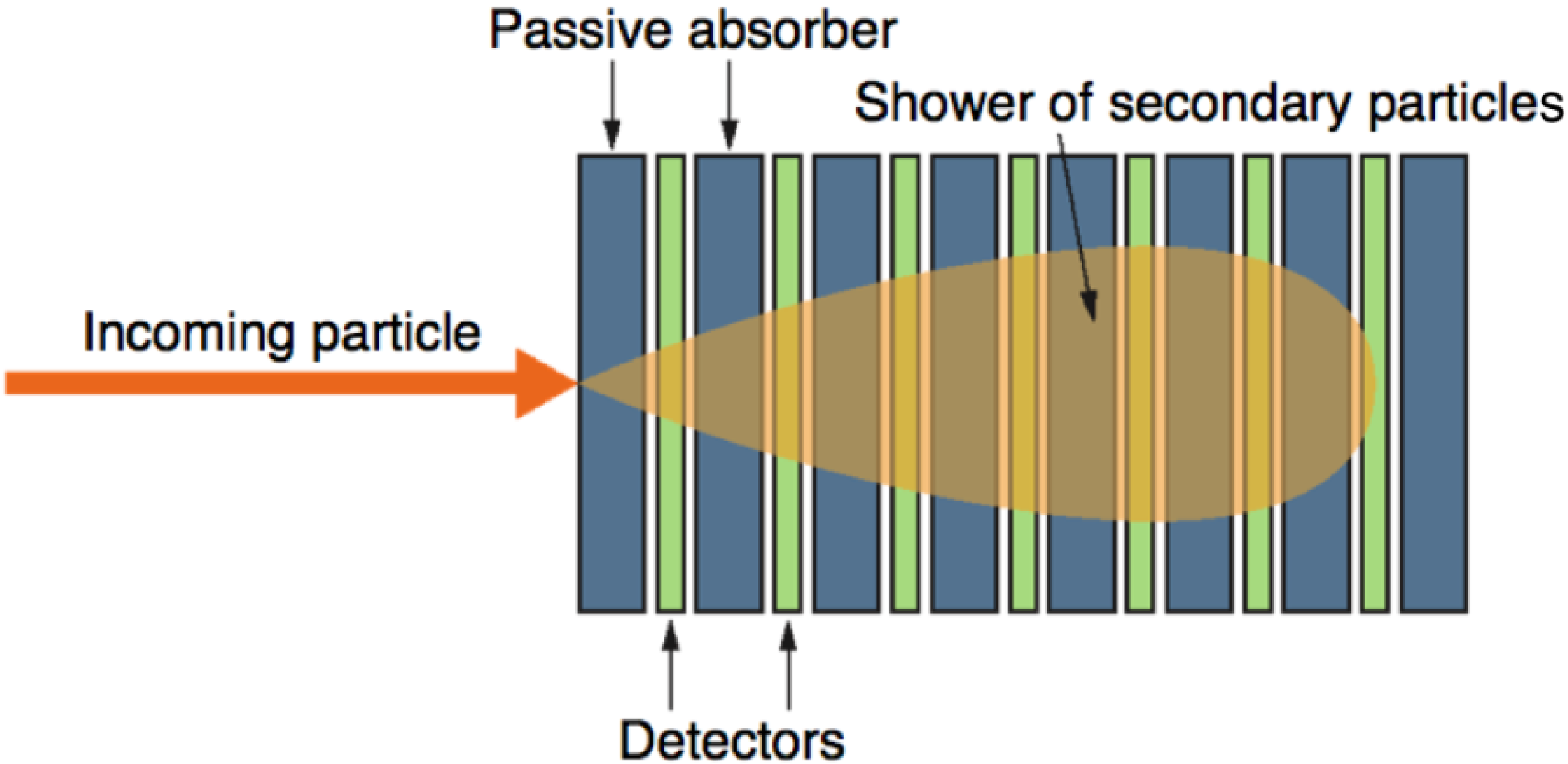
$$R_M = X_0 \left(\frac{21 \text{ MeV}}{E_c} \right)$$

- 90% of the shower energy is contained within a cylinder of radius R_M
- 99% of the shower energy is contained within $3.5\ R_M$

Electromagnetic Calorimeters

- Electromagnetic calorimeters should be several radiation lengths thick to contain the highest energy showers.
- Short X_0 will also restrict the transverse size of showers, facilitating transverse segmentation.
- The ionization energy deposited by electrons and positrons in the shower is proportional to the incident energy.

Sampling Calorimeters



Energy resolution is dominated by the number of photoelectrons detected:

$$\frac{\sigma_E}{E} \propto \frac{\sigma_N}{N} \approx \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E}}$$

Sampling Calorimeters

- Sampling calorimeters can be made rather compact
  - Lead/scintillator, $X_0/\rho \sim 0.56 \text{ cm}$
  - Tungsten/silicon, $X_0/\rho \sim 0.35 \text{ cm}$
  - A depth of 20 radiation lengths is only 11.2 cm or 7 cm, plus the thickness of scintillator.
- Sampling calorimeters can be constructed with some very clever geometries.
- Not all the energy deposited in the detector is measured which degrades the energy resolution.
- A *homogeneous* calorimeter is sensitive to all ionization deposited in the calorimeter volume.

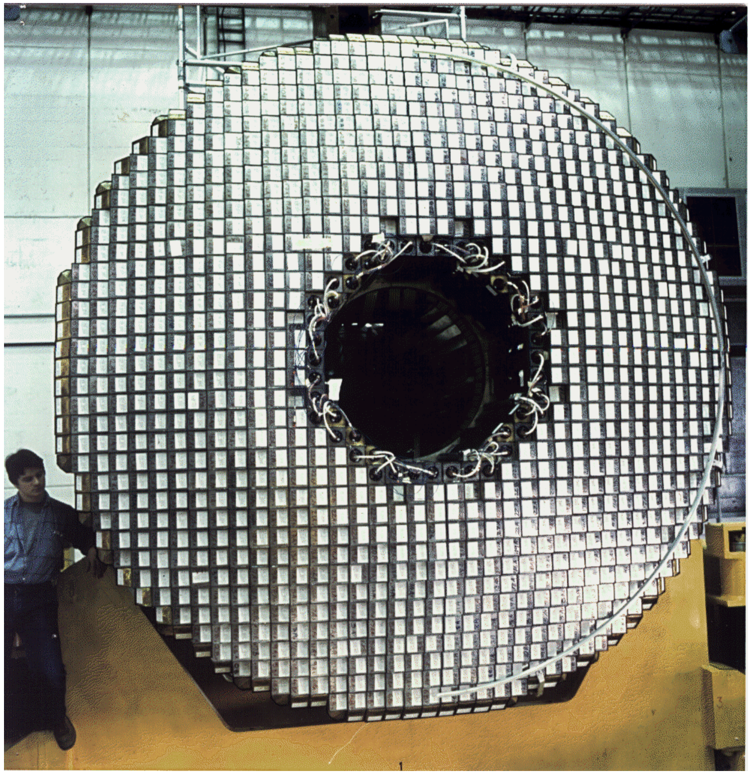
Homogeneous Calorimeters

- If a scintillator is dense enough and large enough, it can contain the entire electromagnetic shower.
- Examples:
  - Bismuth germinate ($Bi_4Ge_3O_{12}$) – BGO, $\rho = 7.13\ \mathrm{g \cdot cm^{-3}}$
  - Barium Fluoride (BaF_2), $\rho = 4.88\ \mathrm{g \cdot cm^{-3}}$
  - Cerium Fluoride (CeF_3), $\rho = 6.16\ \mathrm{g \cdot cm^{-3}}$
  - Lead Tungstate ($PbWO_4$), $\rho = 8.28\ \mathrm{g \cdot cm^{-3}}$

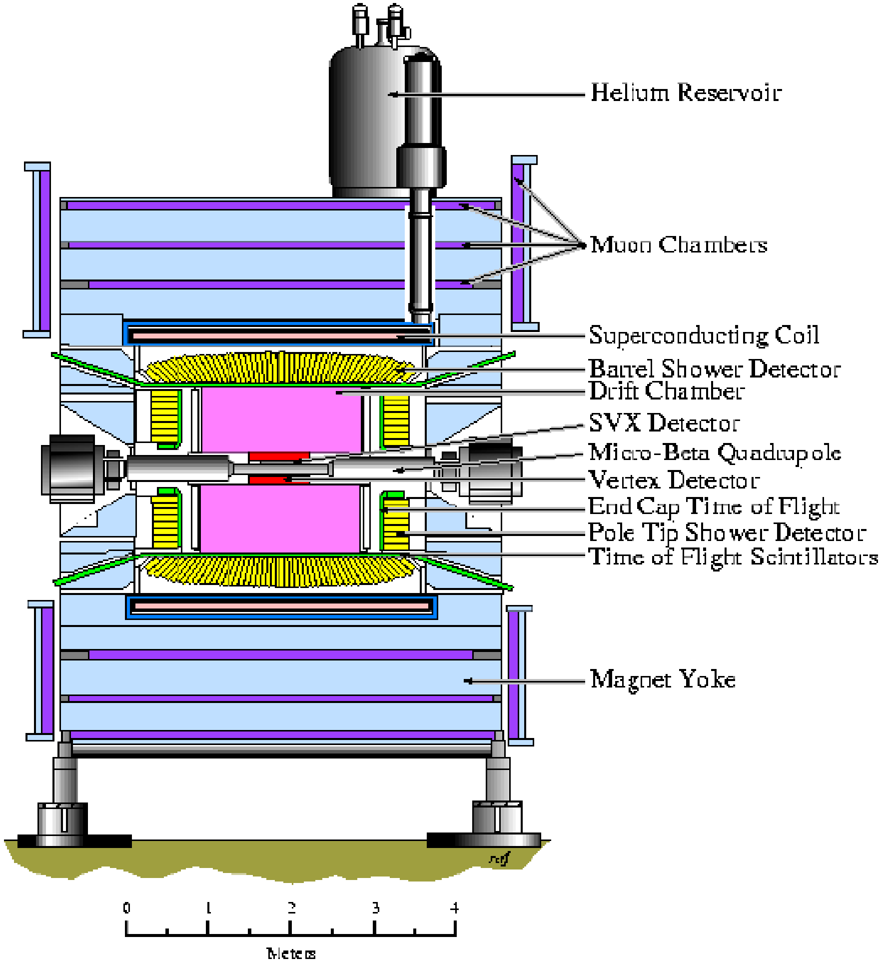
Lead Glass Calorimeters

- Lead glass is very dense ($\rho \sim 4\ \mathrm{g \cdot cm^{-3}}$)
- It is NOT a scintillator
- Its index of refraction is about 1.7
- Any electron with $\beta > 0.588\ c$ will emit Cherenkov light
- This corresponds to $E_c \sim 0.63\ \mathrm{MeV}$

Examples of Electromagnetic Calorimeters

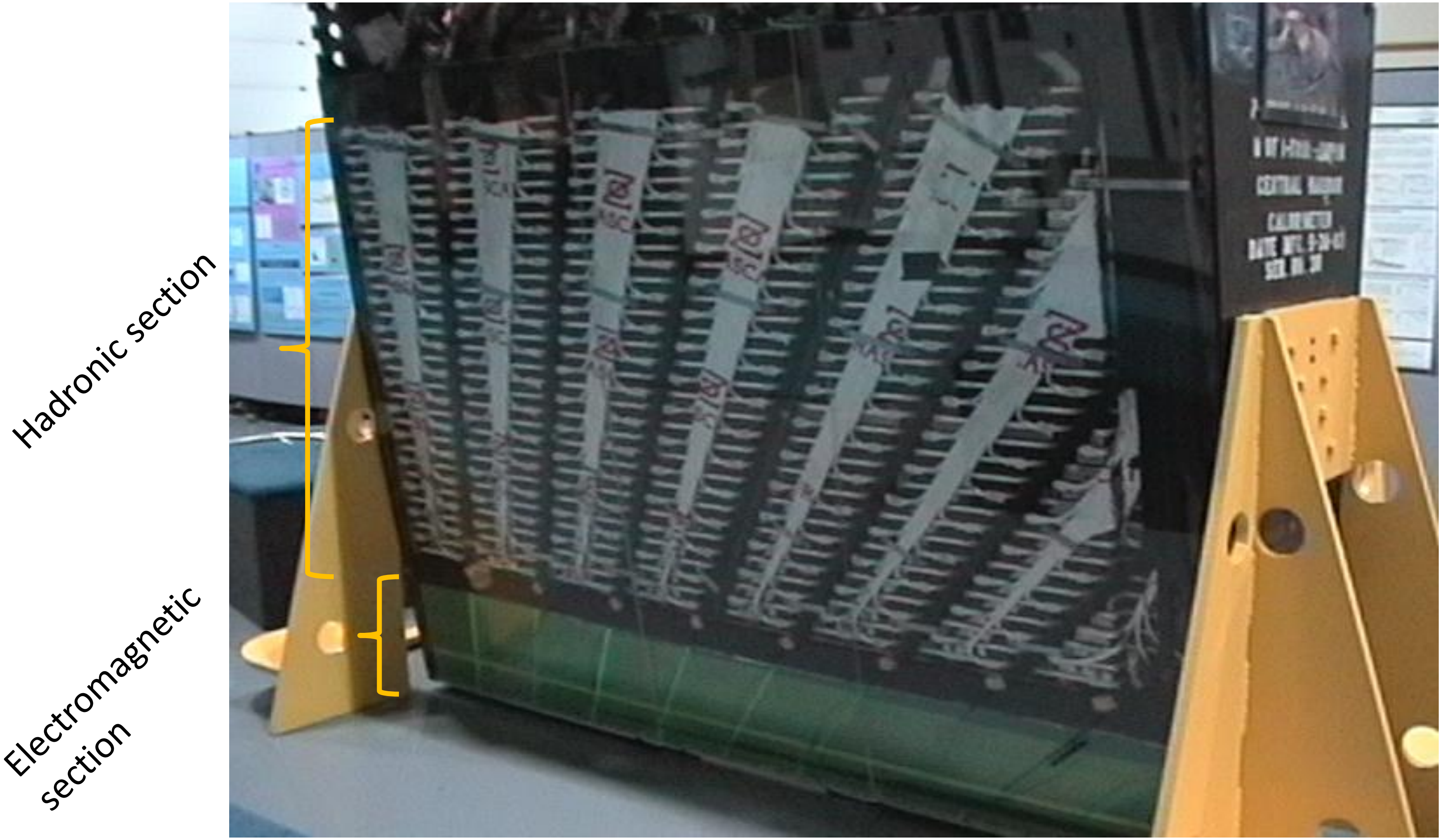


OPAL electromagnetic
end-cap calorimeter
(at CERN in the 1990's)



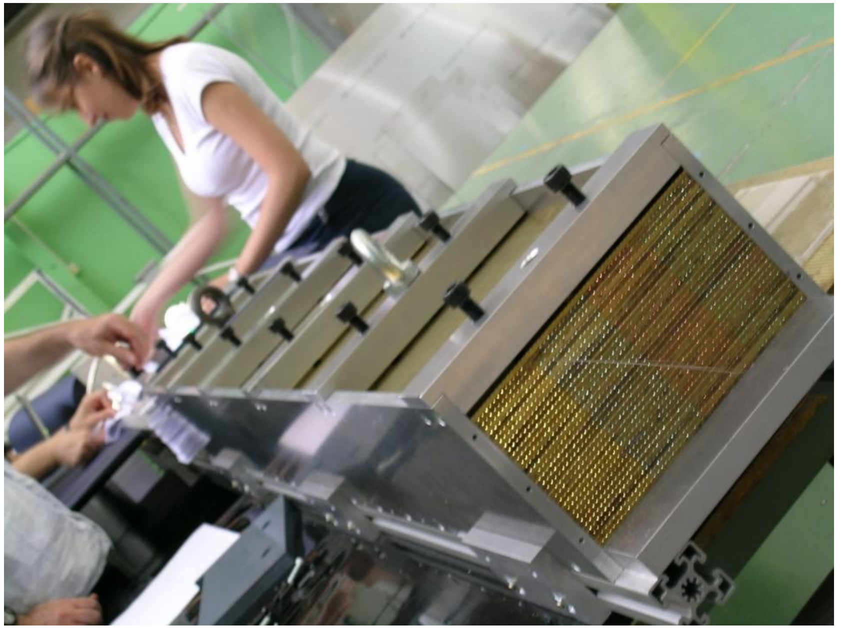
CLEO II Detector
(at Cornell in the 1990's)

Examples of Electromagnetic Calorimeters



Examples of Electromagnetic Calorimeters

- A “spaghetti” calorimeter:



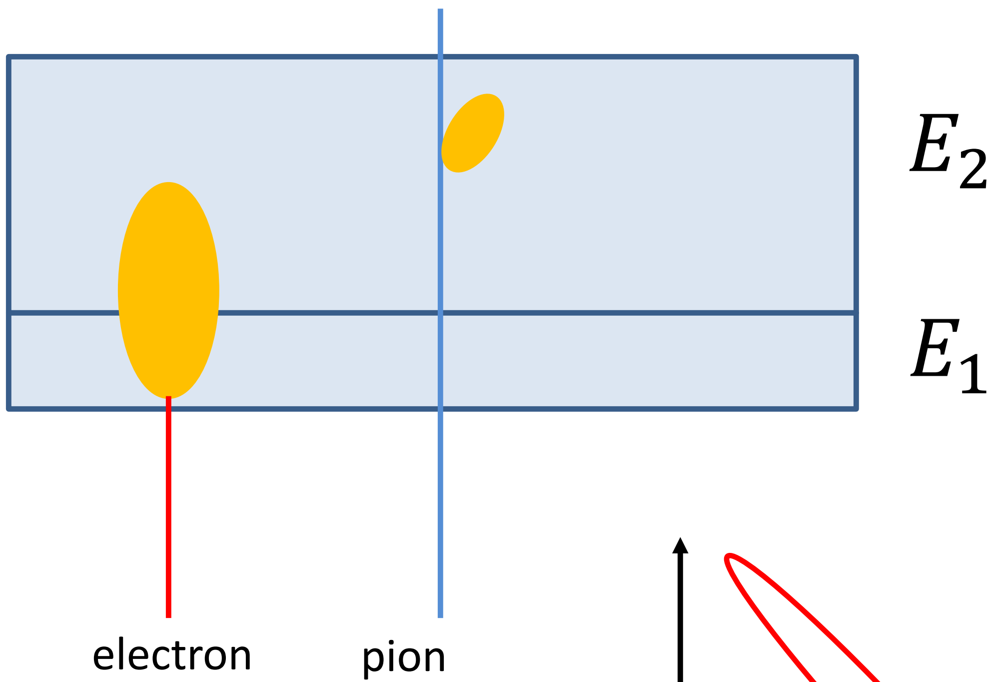
(ALICE zero-degree calorimeter)

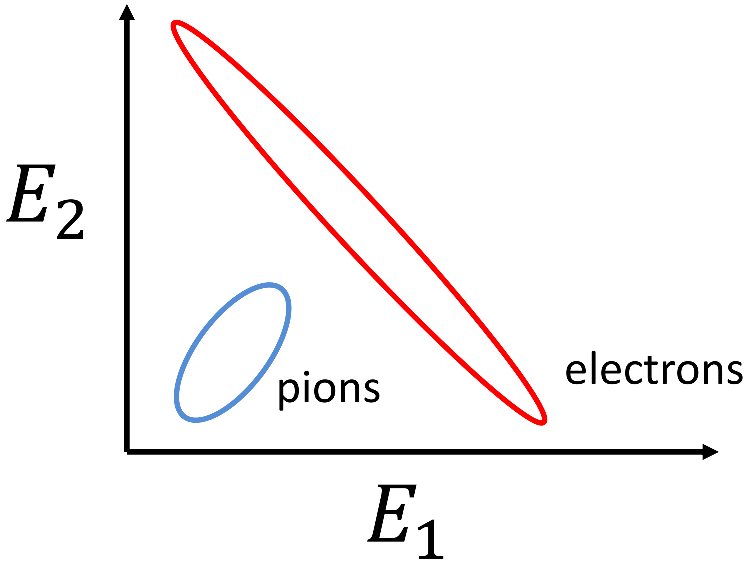
- Quartz fibers are embedded between metal plates.
- Electrons emit Cherenkov light which propagates to the ends of the fibers

Longitudinal Segmentation

- Even limited longitudinal segmentation can be very useful for electron identification.
- Both electrons and charged pions produce tracks leading into the calorimeter
- Electrons will shower but pions will mostly just deposit ionization energy
- A calorimeter with two layers can help to distinguish between electrons and pions.

Longitudinal Segmentation



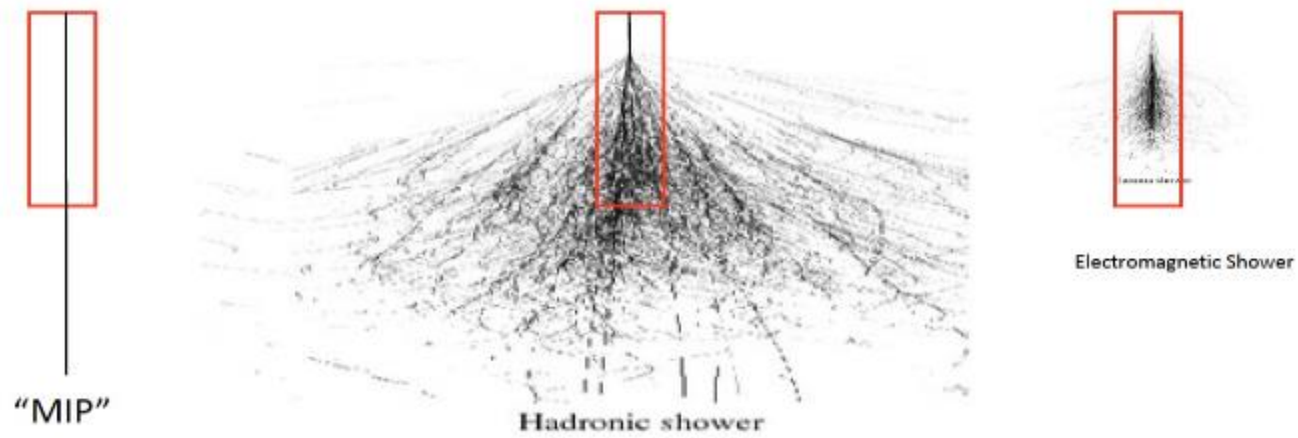


This is difficult to realize with homogeneous crystal calorimeters.

Hadronic Calorimeters

- Same idea except that the shower size scales with the nuclear interaction length, λ_I which is much longer than X_0.
- Hadronic showers are not as uniform as electromagnetic showers.
  - Fewer secondary particles
  - More random secondary particle production
  - Large fluctuations in deposited energy
  - Multiple scattering

Hadronic Calorimeters



- Fluctuations in the number of π^0 produced lead to large observed energy fluctuations.
- Neutral pions decay immediately to $\gamma\gamma$ which deposit all their energy in localized electromagnetic showers.