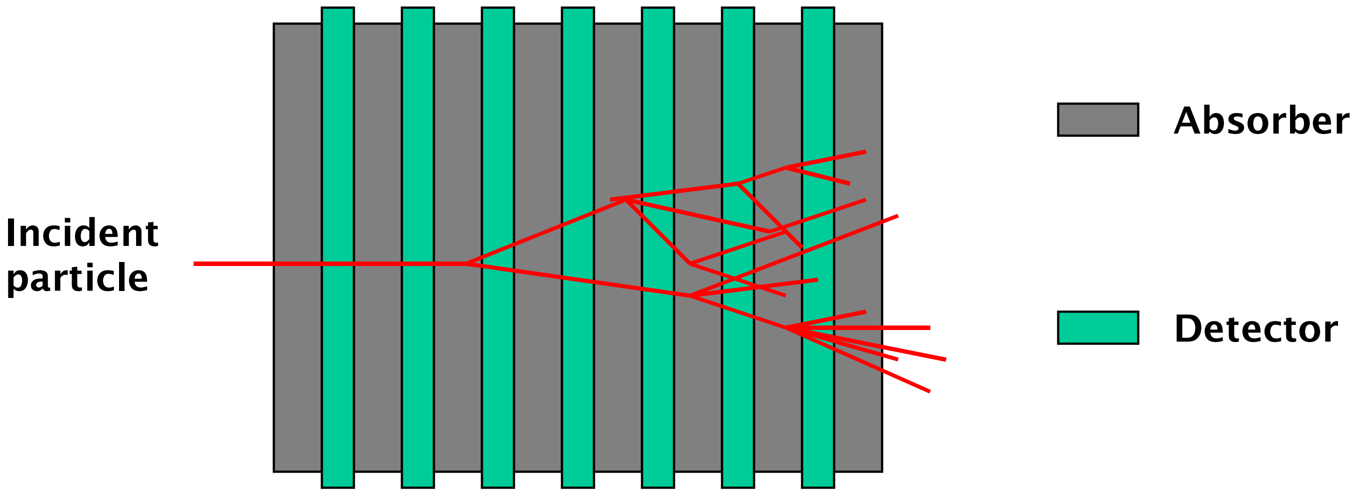
Last Lecture 1) Momentum measurement
2) Semiconductor detectors

Today's Lecture: 1) Electromagnetic and hadronic showers
2) Calorimeter design



What is a Calorimeter?

A device for measuring energy

Charged AND NEUTRAL particles incident on dense material deposit energy, which must be turned into a measurable signal

In total contrast to tracking detectors, we want particles to deposit all of their energy in the calorimeter, so we can detect and measure it, e.g. by producing ionisation or scintillation

For a good calorimeter, the measured signal should be linearly proportional to the incident particle energy

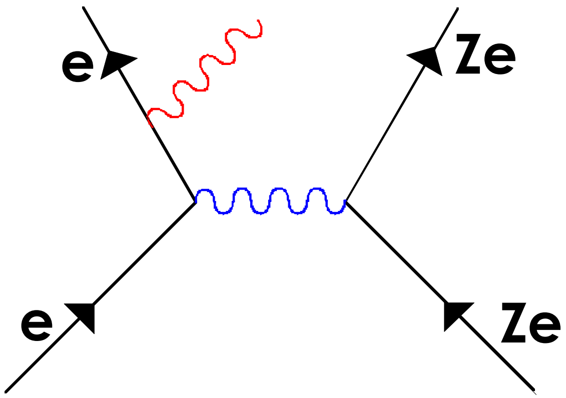
Techniques differ for electromagnetic / hadronic calorimetry

FIRST: How EM and HAD particles interact with matter

Interactions of Electrons in Matter

- Bremsstrahlung radiation from acceleration by nuclei
- Strongly dependent on particle mass
- Dominant energy loss for low mass particles (electrons) at high energy

$$\sigma \approx \frac{1}{m^4}$$



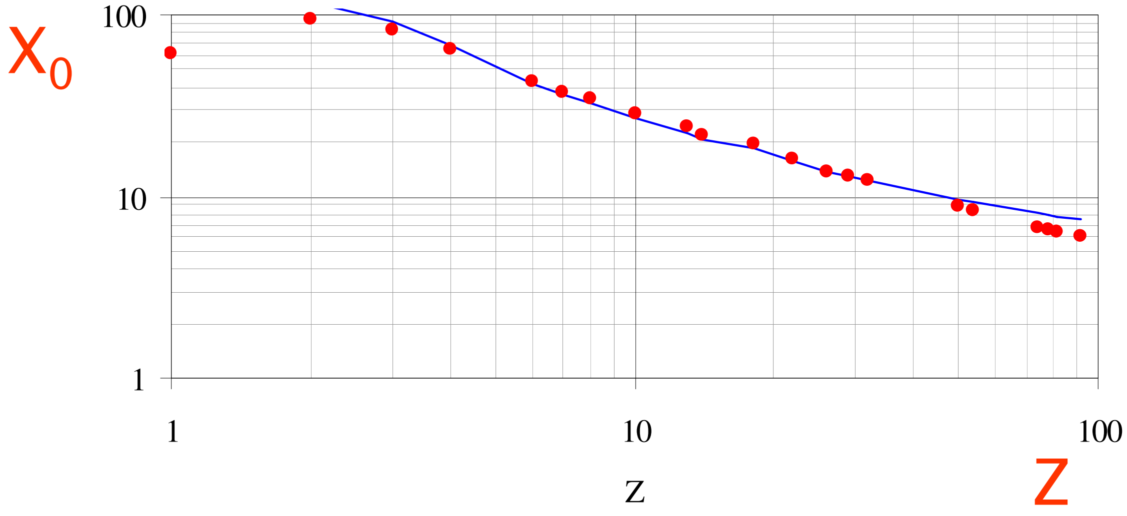
Define “radiation length” X_0 = mean distance over which electron energy reduced by bremsstrahlung to a fraction 1/e of its start value

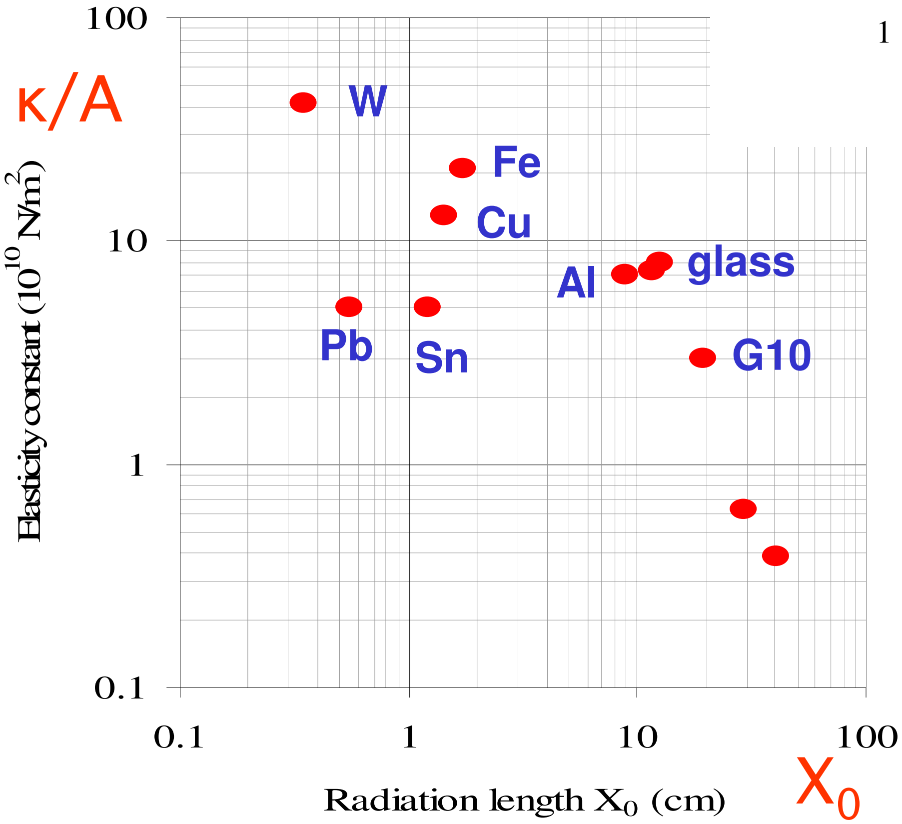
$$E = E_0 e^{-x/X_0}$$

- X_0 depends on material properties roughly as $X_0 = \text{const.} \times (A / Z^2)$
- If material thickness expressed in X_0, radiation loss is independent of material

Some Radiation Length Data

$$X_0 \approx 180 \frac{A}{Z^2} \text{ g/cm}^2$$





Z^2 expresses charge of scattering sources,

1/A ~ expresses the number of sources per unit volume

Rate of energy loss ~ $1/X_0$

High Z is good for a calorimeter

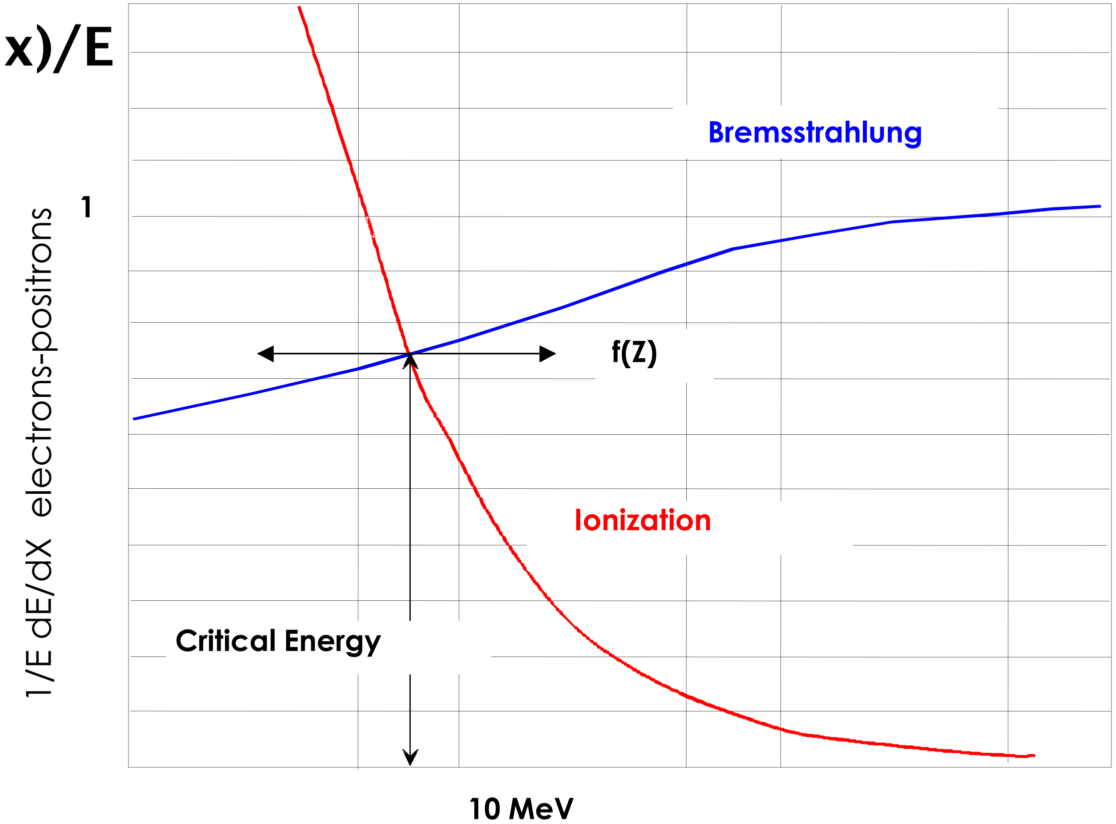
The Critical Energy

"Critical energy" is that for which Bremsstrahlung and ionisation losses become equal (will be important later)

Ionisation energy loss ~ $Z/(A.\beta^2)$ (Bethe Bloch)

Bremsstrahlung ($\sim Z^2$) has stronger Z dependence but little projectile energy dependence

(dE/dx)/E



Projectile energy

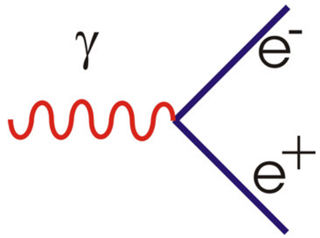
Very roughly, electron critical energy $E_c \sim 550/Z$ MeV

Energy Loss for Photons

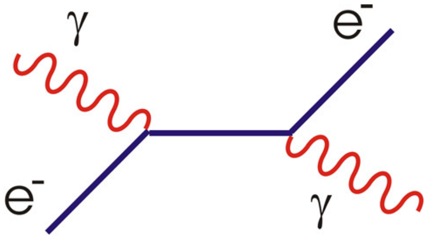
Photons interact in 3 main ways:

1) Pair production (high energy)
2) Compton scattering (low energy)
3) Photoelectric absorption (even lower energy)

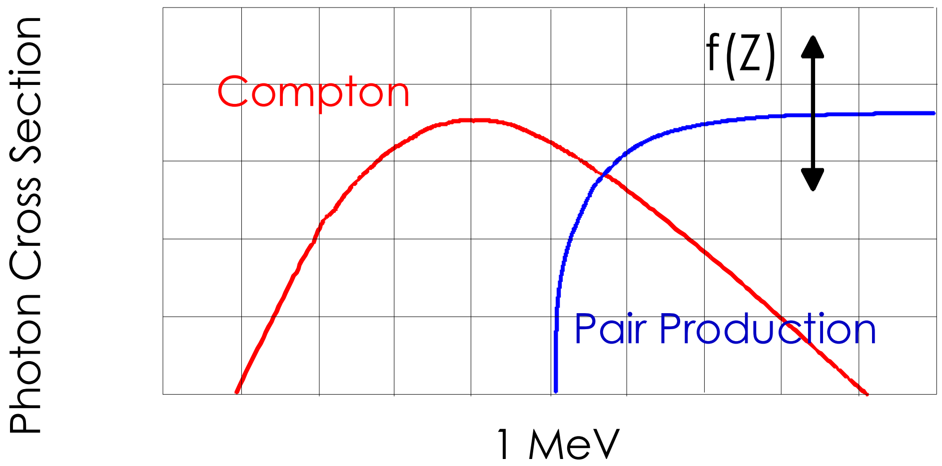
1)



2)



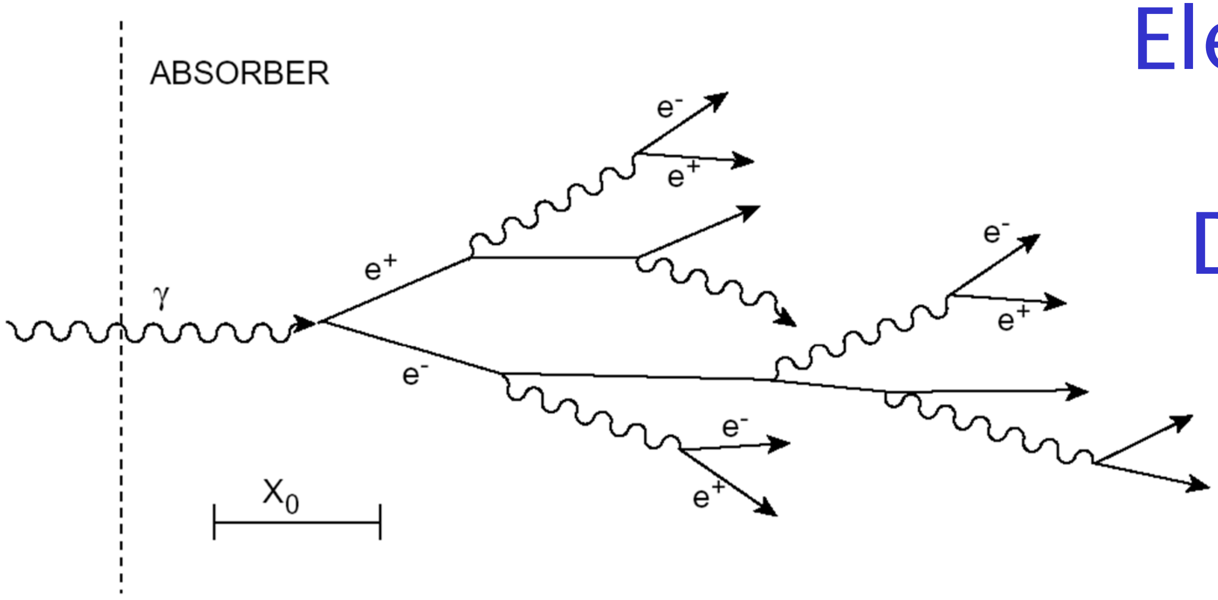
3) $$\gamma + A \rightarrow A^* + e^-$$



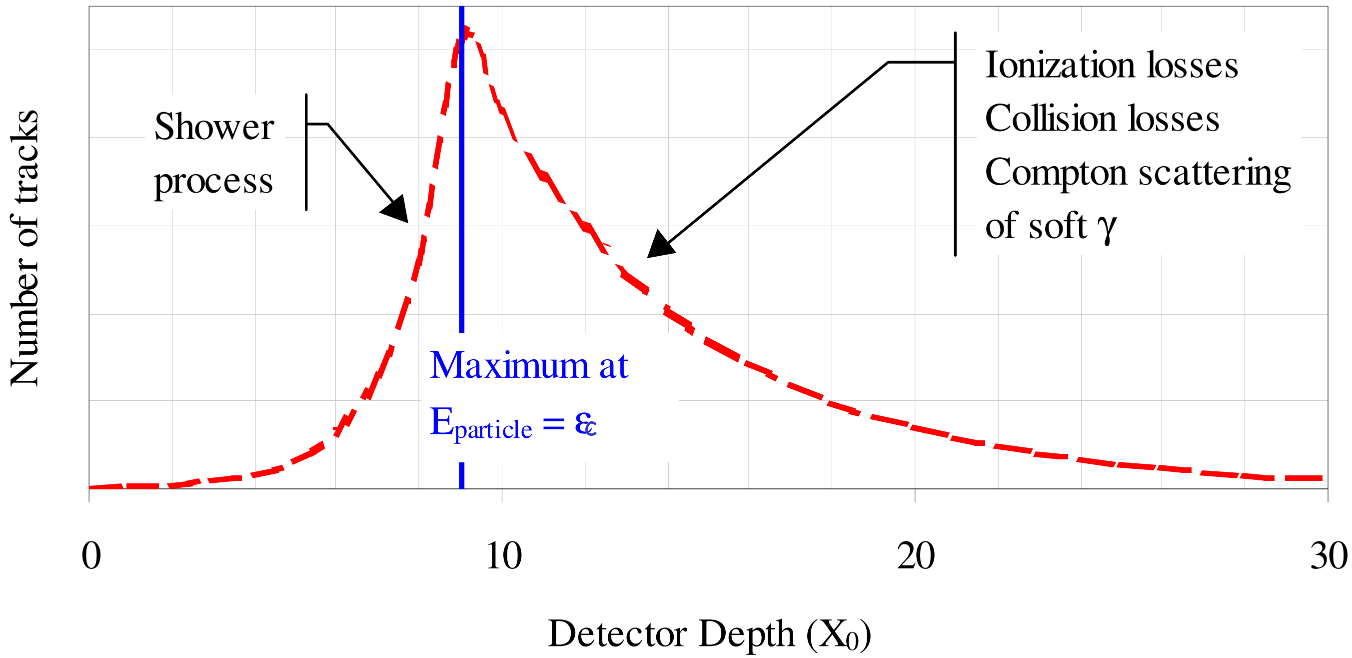
Mean free path for pair production $\gamma \rightarrow e^+e^-$ in a material is ~9/7 X_0 (similar to Bremsstrahlung)

At high energy, electron Bremsstrahlung plus photon pair production usually lead to an **"electromagnetic shower"**

Electromagnetic Shower Development

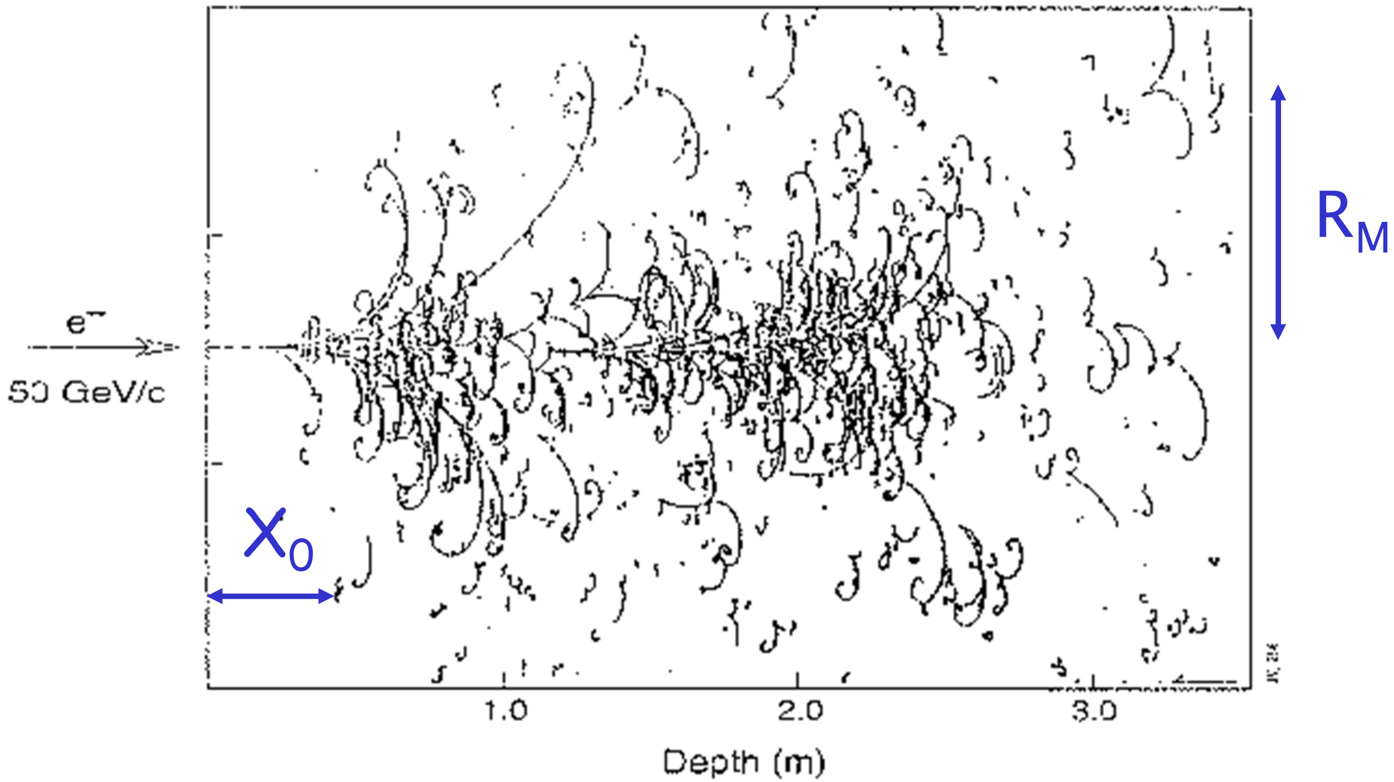


Shower maximum when shower particles on average have an energy equal to the critical energy



An Electron Shower in a Bubble Chamber

Big European Bubble Chamber filled with Ne:H_2 = 70%:30%,
3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron



Lateral spread generated mainly by multiple scattering ~ energy independent

Molière radius: $R_M = X_0 \cdot 21\text{MeV} / E_C$ characterises shower width → ~90% of shower energy within this radius

Summary of an Electromagnetic Shower

- Bremsstrahlung and pair production (above critical energy)
  - Shower deposits ~const energy per radiation length
  - Each step number of particles in shower ~doubles
    and energy per particle ~halves
  - Emission angles small, so narrow shower develops
  - Shower width mainly from multiple scattering
- When energy falls below the critical energy
  - Ionisation and collisions dominate energy loss
  - Shower stops over relatively short distance

Hadronic Showers

Much more complicated than electromagnetic showers
Hadrons interact strongly as well as ionising the sampling material, so nuclear reactions become an important energy loss mechanism.

Nuclear interaction length, λ: Mean distance before hadron has inelastic nuclear interaction, $N(x) = N(0)\, e^{-x/\lambda}$ [$\lambda >> X_0$]

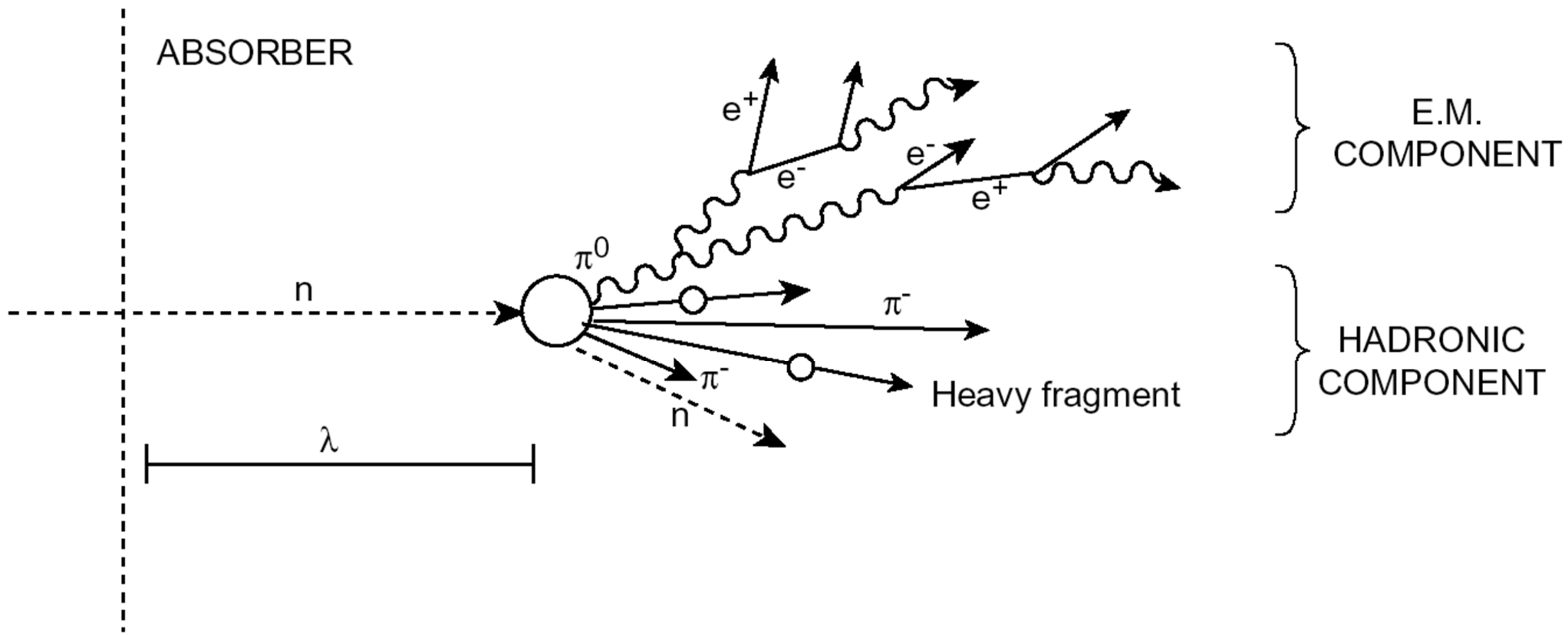
Roughly, $\lambda \sim$ **35 $A^{1/3}$ g cm^{-2}**, quite long even for dense materials, so **hadronic showers are longer and broader than EM showers**

Other difficulties compared with electromagnetic showers:

- Unmeasured (or poorly measured) energy caused by neutrons **exciting or breaking up nuclei**.
  Also makes hadronic showers broader than EM showers.
- Large component from $\pi^0 \rightarrow \gamma\gamma$
  Hadronic showers have an electromagnetic core.

Development of Hadronic Showers

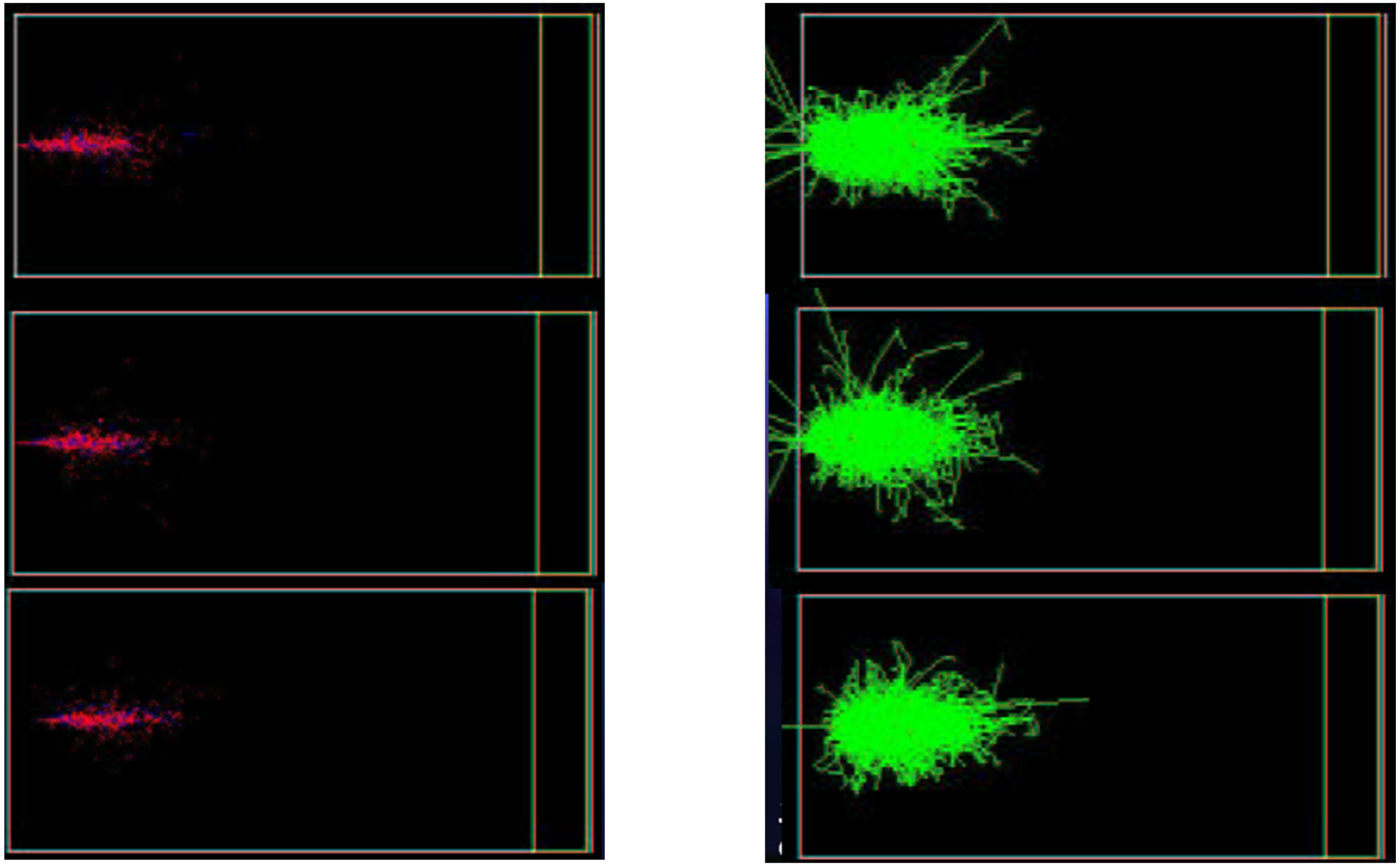
Nuclear interactions lead to large energy loss, but have long λ (λ~50 cm for protons in lead)



Simulation of Hadronic Shower

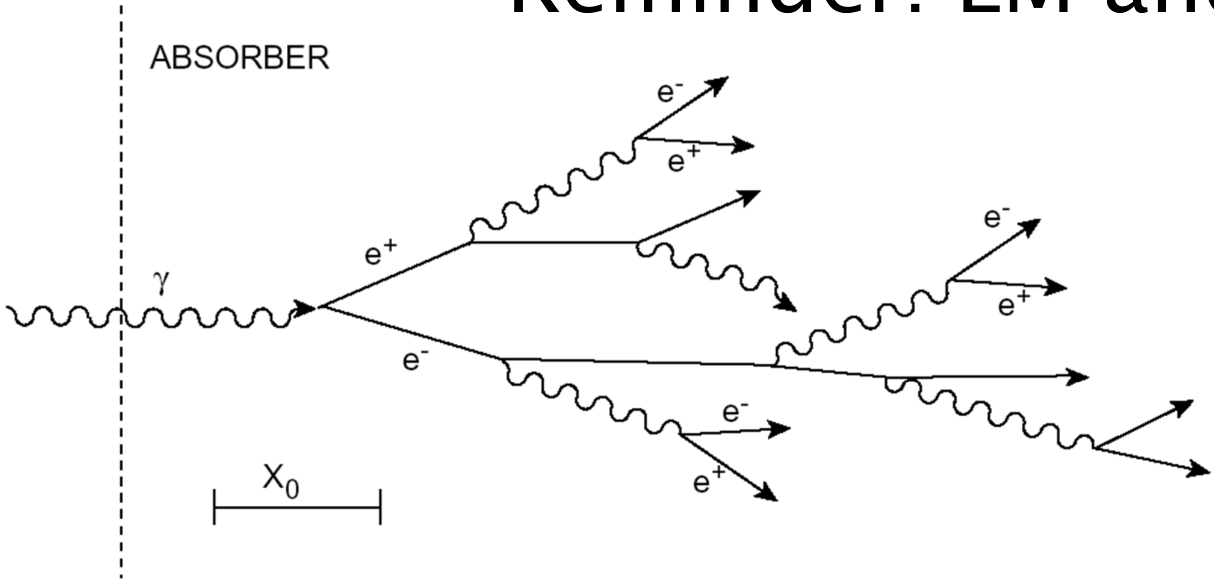
20 GeV hadronic showers in copper

Charged particles | Full shower



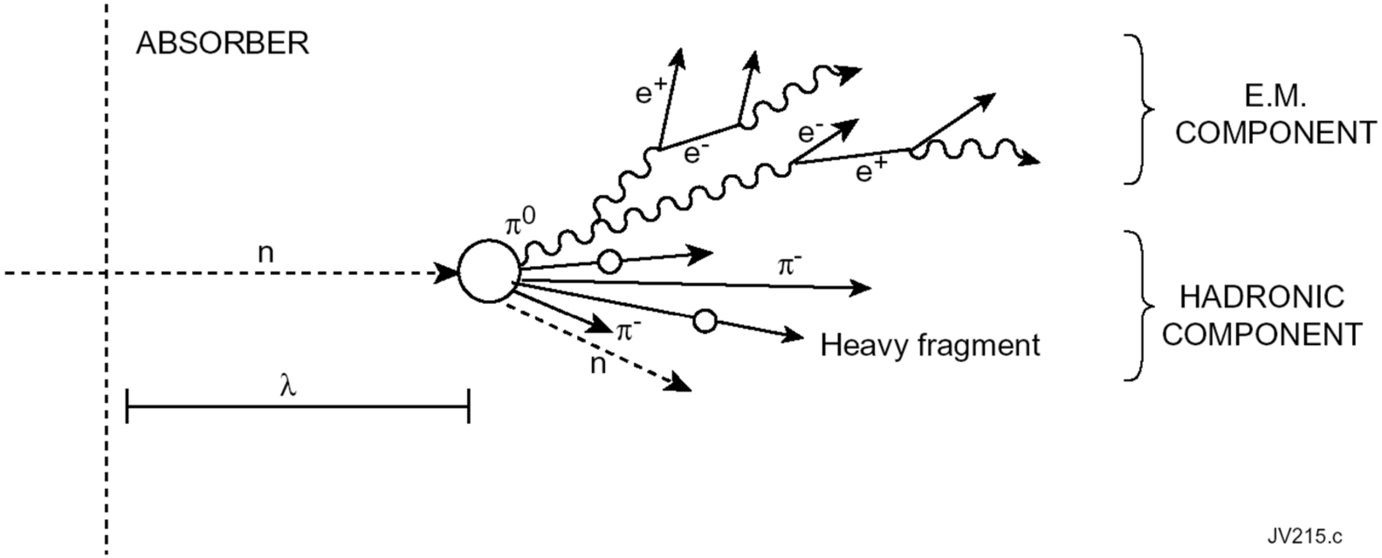
Large transverse component, especially from neutrals

Reminder: EM and HAD showers



Electromagnetic Shower

Hadronic Shower



Have to detect and measure particles in showers

Basics of Calorimeter Design

Calorimeters require:

- dense **ABSORBER** material in which to create shower
- **SAMPLER** as a means of measuring the shower content and getting a signal out

1) "Homogeneous" Calorimeters:

Entire detector volume acts as both absorber and signal source
Dense materials usually generating light (e.g. crystals, glasses)
Good resolution, but expensive and hard to grow big crystals
Sometimes used for electromagnetic calorimetry

2) "Sampling" Calorimeters:

Alternating layers of absorber and sampler
Sample ionisation or scintillation from charged shower compt.
Used for all hadronic and many electromagnetic calorimeters

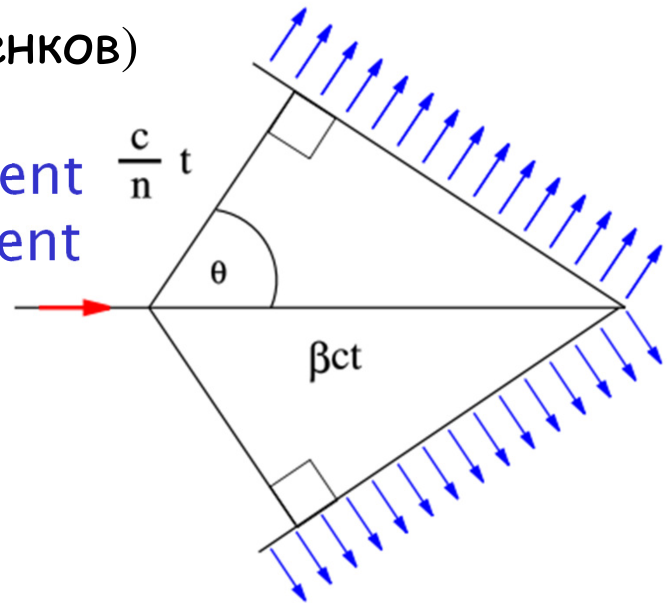
Homogeneous Calorimeters

Use special optical properties of crystals or glasses to generate detectable signal from electrons and photons in shower (scintillation light or Cherenkov radiation), which passes through rest of detector to be collected and read out

(alternative spellings: Cerenkov, Čerenkov, Черенков)

Cherenkov radiation:

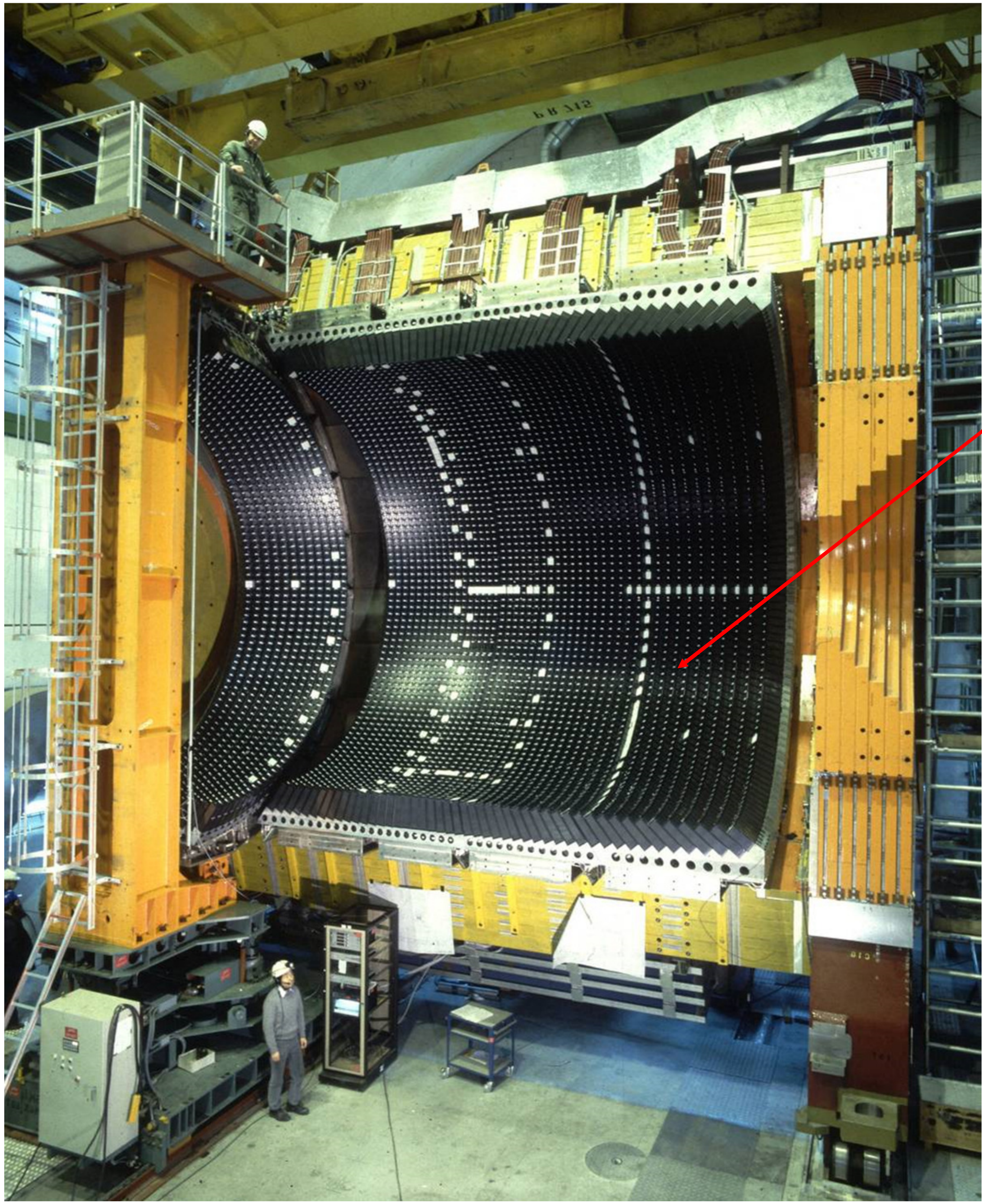
- Charged particle with $v > c/n$ emits coherent radiation at an angle $\cos\theta = 1/n\beta$ to incident particle → ring of photons in detector
- Can be used for particle identification



Application to Crystal Calorimeters:

- Electrons and positrons in electromagnetic shower emit Cherenkov radiation at optical wavelengths
- Radiation collected in photomultiplier tubes
- Total light amplitude collected is proportional to total energy deposited by incident e or γ

Example Homogeneous Calorimeter

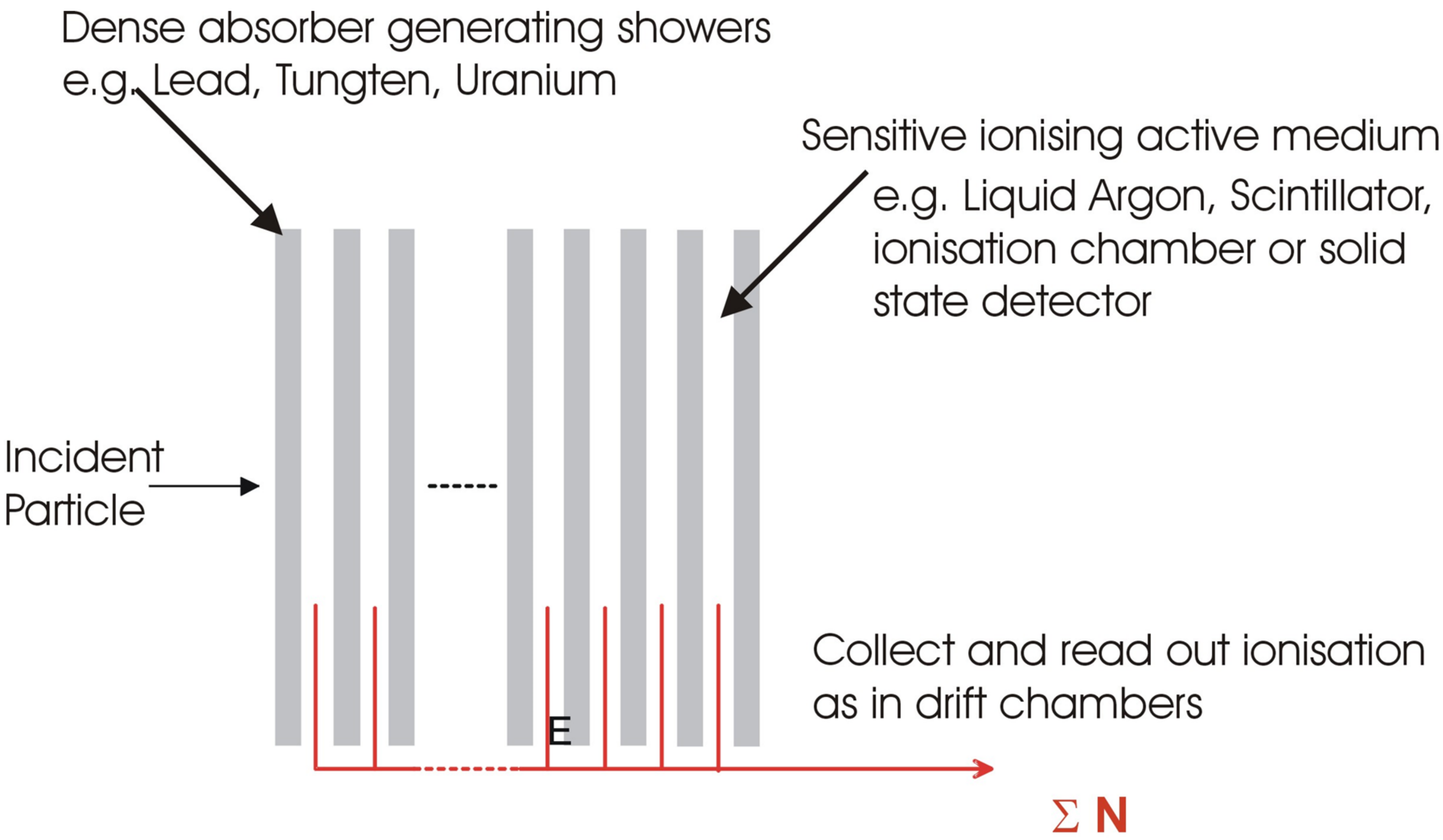


Individual lead glass blocks

- OPAL EM Calorimeter

Also used for electromagnetic calorimeter in CMS (lead tungstenate crystals)

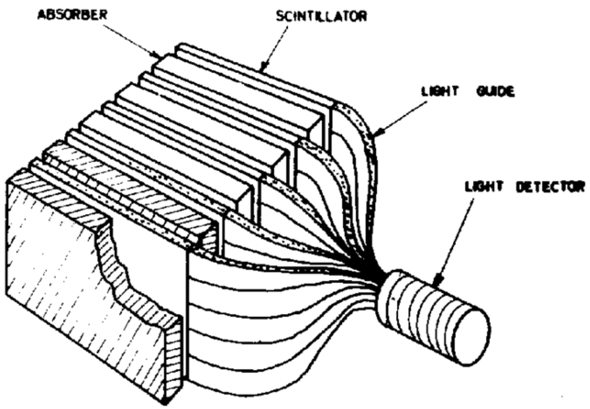
Sampling Calorimeters



- (Ionising or scintillating) charged component of shower sampled
- Can fill large and awkward volumes at acceptable cost
- **Only a fraction of deposited energy is sampled**

Examples of Sampling Calorimeter Designs

Scintillator readout



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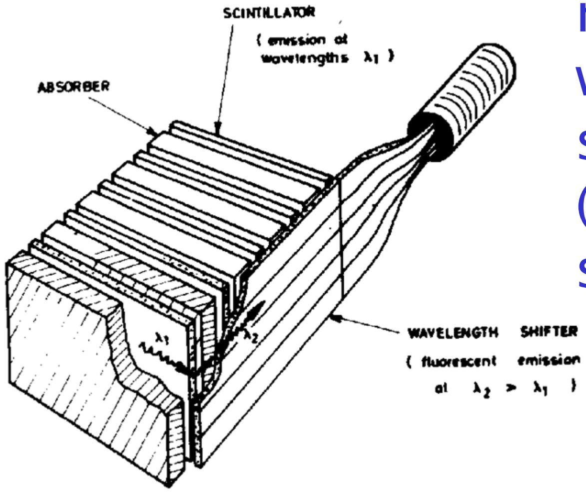
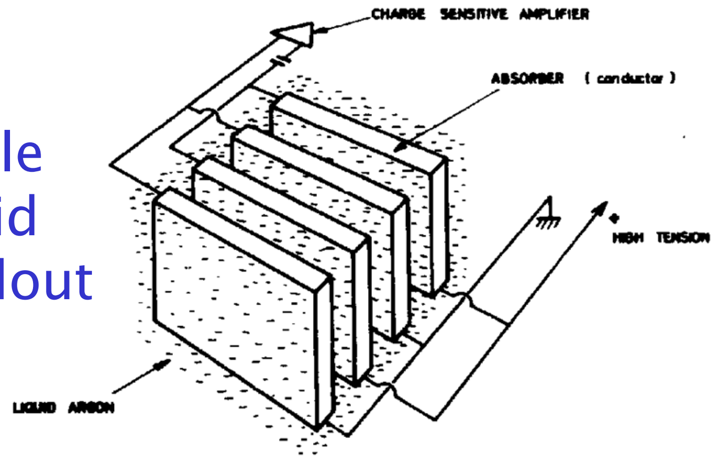


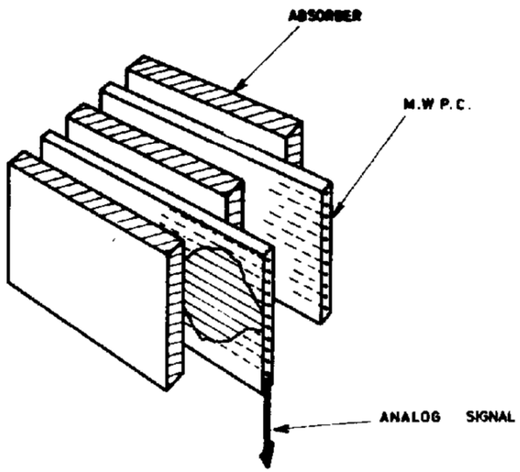
b)

Scintillator readout with wavelength shifter bars (or wavelength shifting fibres)

Noble liquid readout



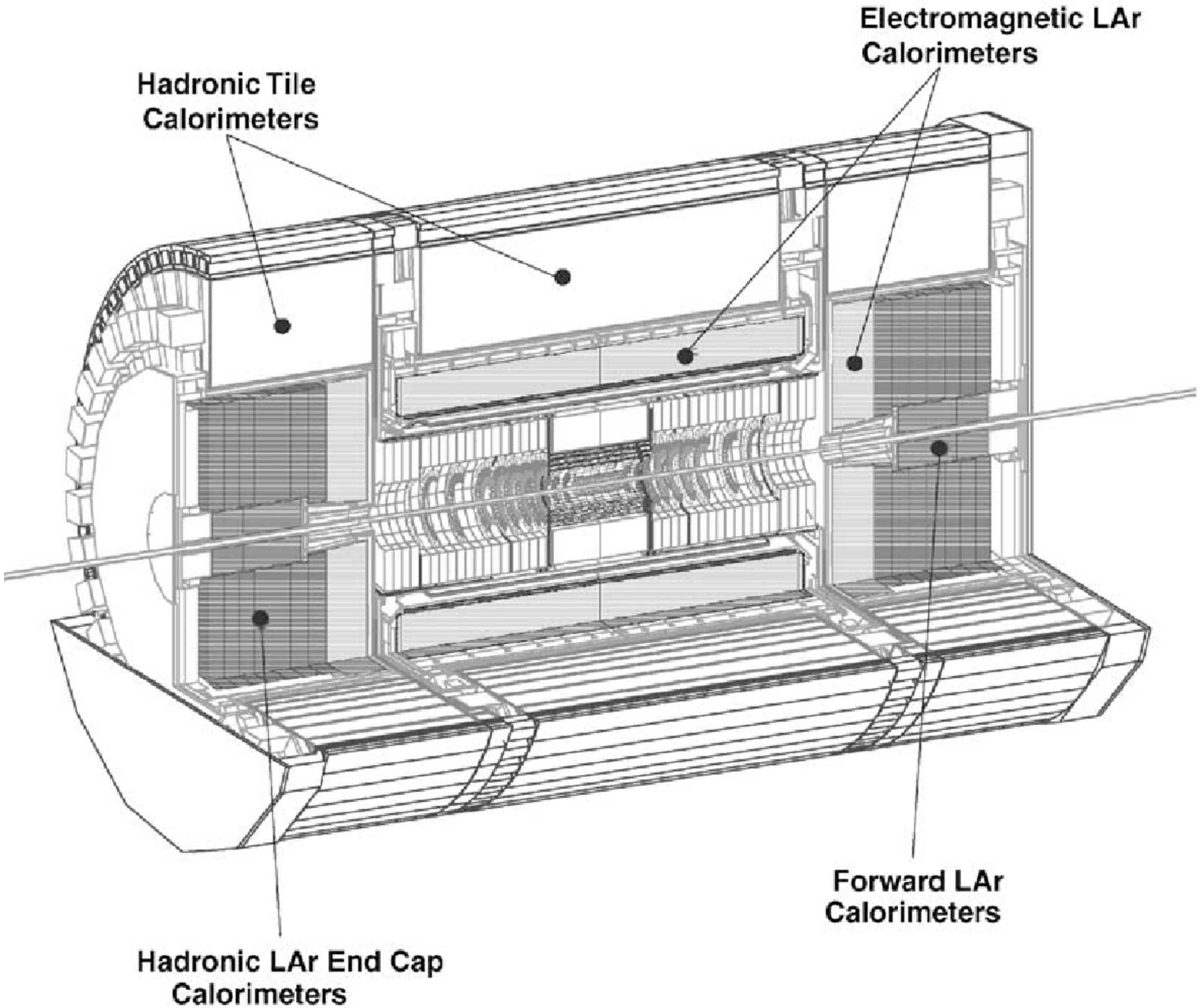
c)



d)

Readout with gaseous detectors (MWPCs or streamer tubes)

e.g. ATLAS Calorimetry



- EM calorimeter with lead absorbers and liquid argon active material
- Hadronic calorimeter with alternating tiles of stainless steel absorbers and active scintillator (polystyrene)

Calorimeter Resolution

Resolution of a Calorimeter usually considered in 3 parts:

1. $\sigma(E) \propto \sqrt{E}$ 'counting error' due to statistical fluctuations in showering / sampling

2. $\sigma(E) \propto const$ Energy independent error due to electronic noise, pile-up of other events at LHC ...

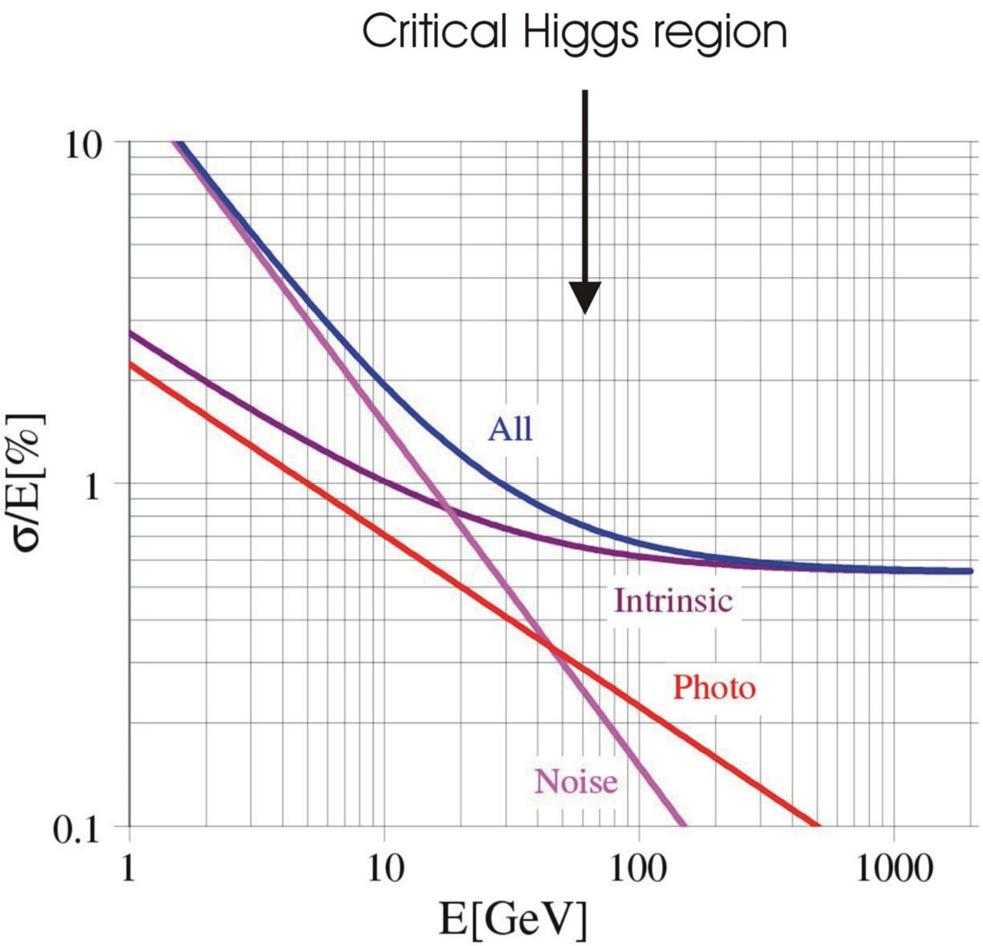
3. $\sigma(E) \propto E$ Losses due to leakage or dead material, systematics such as miscalibration

Usually quoted as a fractional error ($\oplus$ means 'add in quadrature')

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$ (E in GeV)

typically for em calo $a = 0.1, b = c = 0.01$ for had $a \sim 0.4$

Example: CMS



At low E, $\sigma(E)/E \sim 1/E$, dominated by noise, pile-up etc.

At higher E, $\sigma(E)/E \sim 1/E^{1/2}$, dominated by “intrinsic” statistical sampling error

c.f. trackers, $\sigma(p_T)/p_T \sim p_T$

Calorimeter resolution improves with increasing energy
Tracking resolution deteriorates with increasing energy
The two types of detector are often complementary

Next time: Triggering and Data Acquisition

If you are interested in applying for a PhD studentship with the Birmingham Particle Physics Group, please see

http://www.ep.ph.bham.ac.uk/index.php?page=exp/phdentry/index

We are now accepting applications for 2015 PhD entry

Particle Physics Group PhD Open Day, 2.30pm, Wed 12 Nov, PP area on 2nd floor of Physics West

Please contact Dr. Cristina Lazzeroni (PhD Admissions tutor) for further information