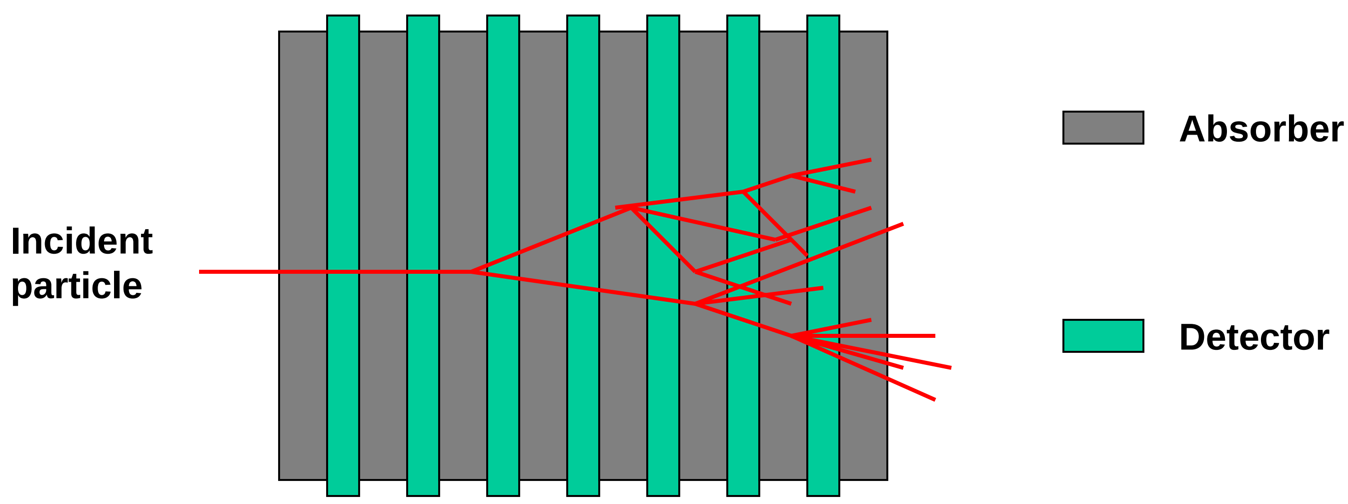
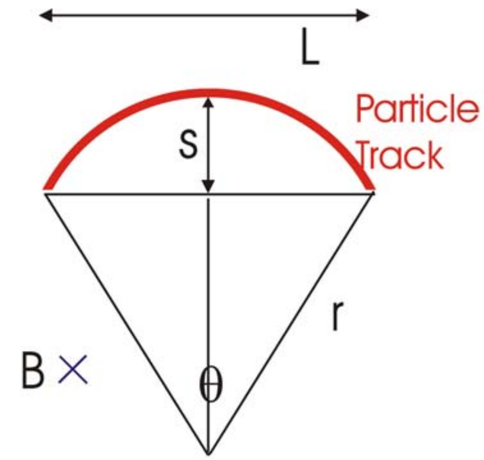
Last Lecture 1) Silicon tracking detectors
2) Reconstructing track momenta

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



Reconstructing track transverse momenta: the Sagitta



- Drift chamber gives a track segment about chord of the circle described by the particle.
- In practice, measure the **sagitta s** in order to reconstruct p_t.

$$s = L^2 / 8r = qBL^2 / 8p_t$$

… hence obtain p_t from s …

$$\sigma(p_t)/p_t = \sigma(s)/s = [8 / (q\,B\,L^2)]\,.\,p_t\,.\,\sigma(s)$$

- resolution degrades α p_t
- σ(s) depends on number of wires (points in track segment)

For an accurate pt measurement, want low p_t

high B field

long chord, L

lots of hits on segment

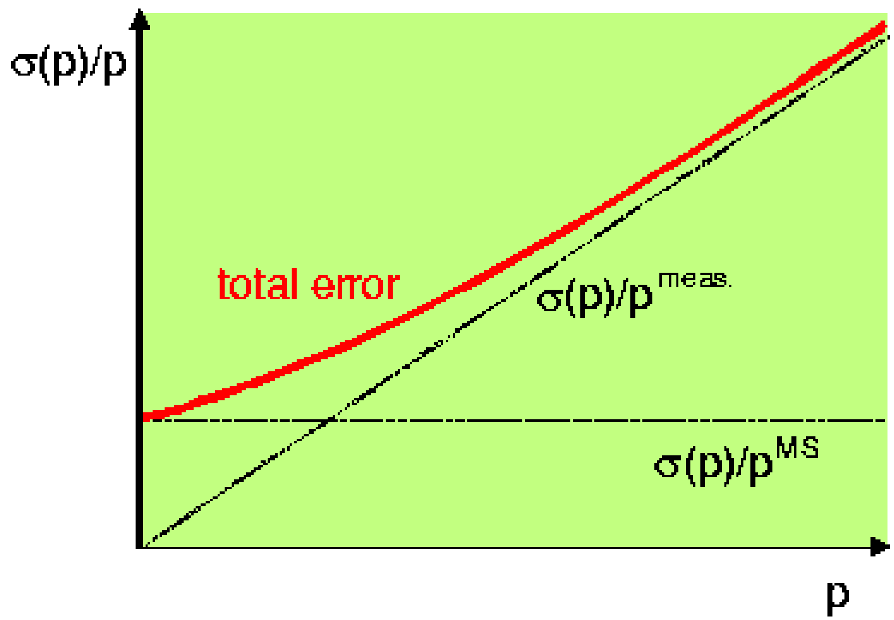
lots of separate segments

Momentum Uncertainty for Trackers

- For high momenta, uncertainty is dominated by sagitta measurement
- As momentum becomes very small, multiple elastic Coulomb scattering takes over -> lots of small deflections in angle, no energy loss
- Error on the momentum measurement is independent of p

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045 \frac{1}{B\sqrt{LX_0}}$$

X_0 is the radiation length of material



If you want precision, minimise dead material e.g. in beampipe!

What is a Calorimeter?

..... **A device for measuring energy!**

Charged <u>AND NEUTRAL</u> particles incident on dense material deposit energy which must be turned into a measurable signal

In total contrast to gaseous tracking detectors, we want particles to deposit all of their energy in the calorimeter, so we can detect and measure it.

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

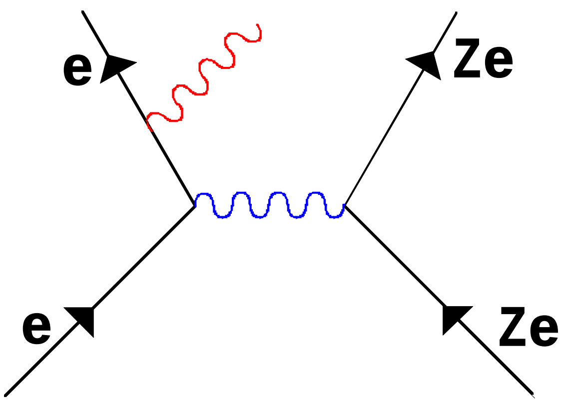
Different techniques for electromagentic and hadronic calorimetry

FIRST: How EM and HAD particles interact with matter...

Interactions of Electrons in Matter

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

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



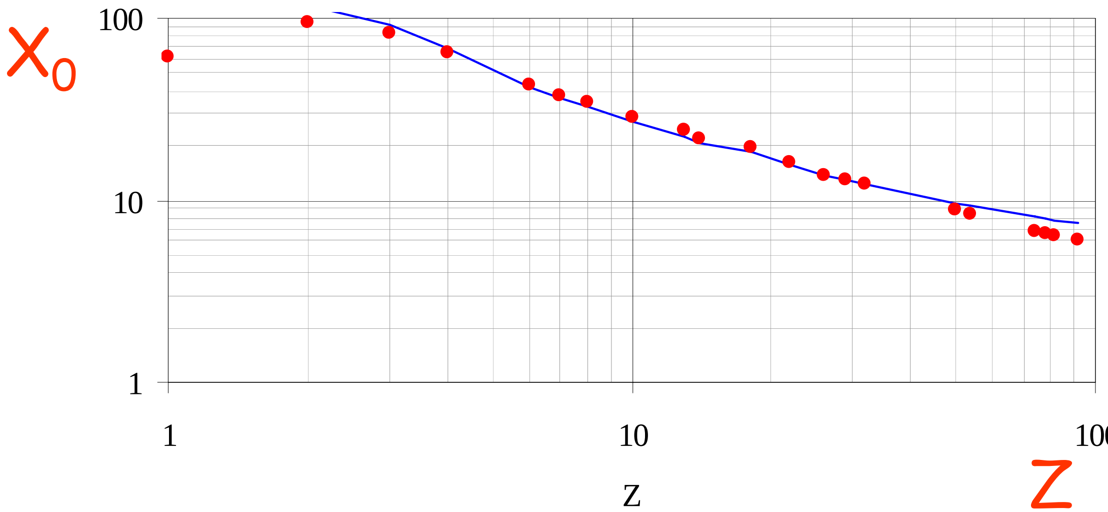
Define `Radiation length' X_0 = mean distance over which electron energy reduced to a fraction 1/e of start value

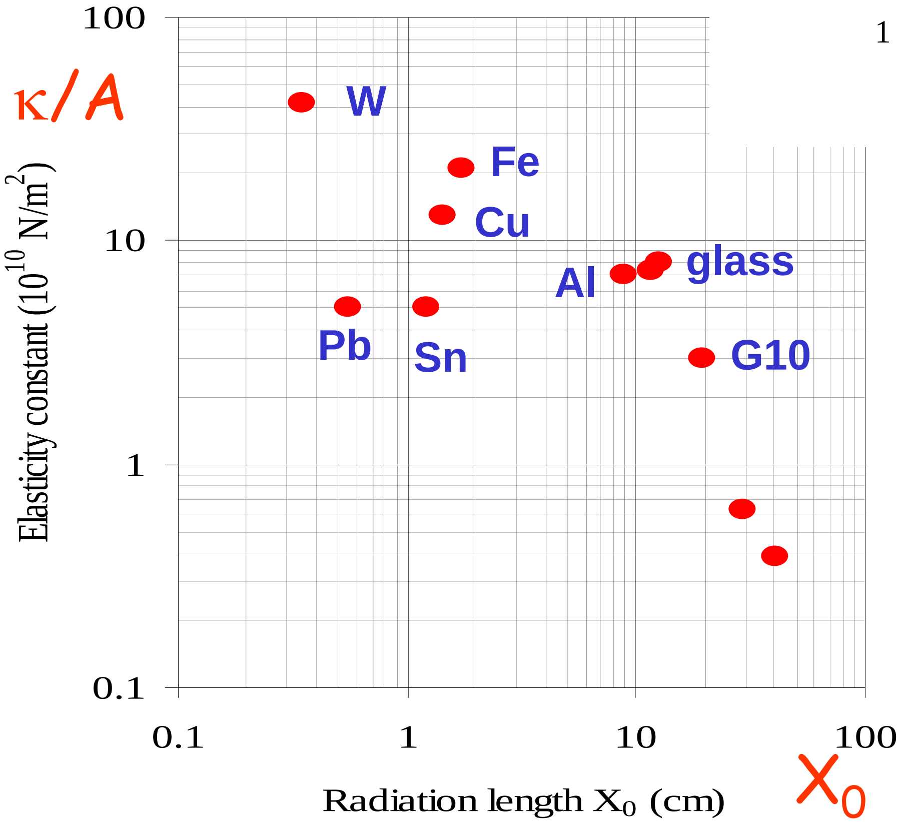
$$E = E_0 e^{-x/X_0}$$

- Apart from incident particle mass, X_0 depends on material properties roughly as $X_0 = \text{const.}\ A / Z^2$
- If material thickness expressed in X_0, radiation loss is independent of material

Some Radiation Length Data

$$X_0 \approx 180 \frac{A}{Z^2}$$





… Z^2 expresses charge of scattering sources,

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

Rate of energy loss ~ $1/X_0$

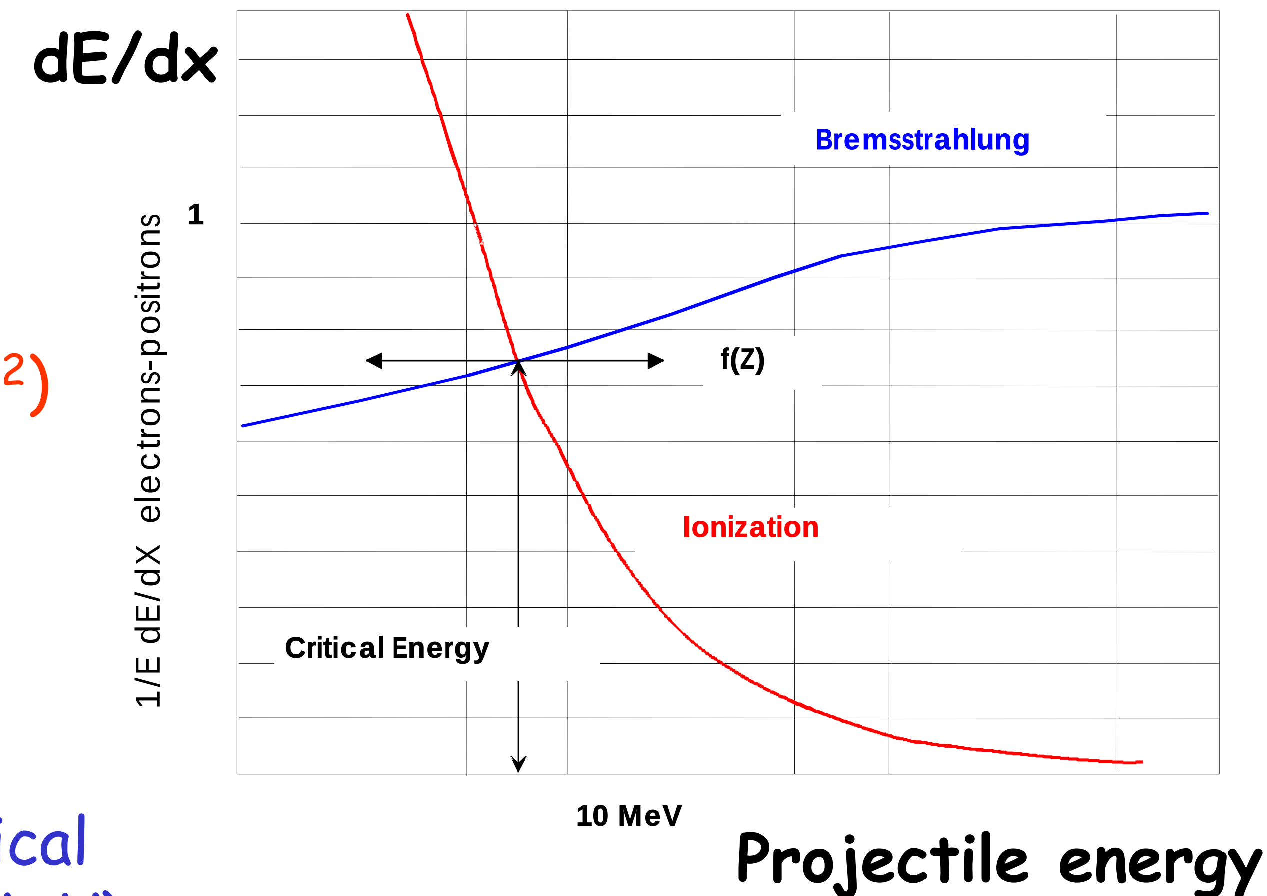
… high Z is good for a Calorimeter!

The Critical Energy

'Critical energy' is that for which Bremsstrahlung and ionisation losses 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



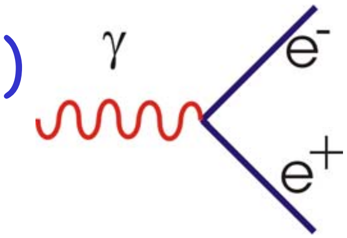
... very roughly, critical energy $E_c \sim 600/Z$ (MeV)

Energy Loss for Photons

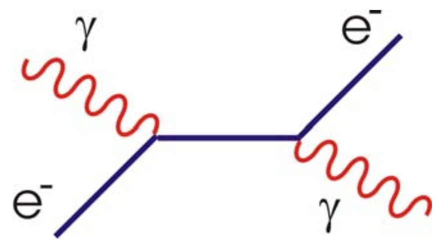
Photons interact in 3 main ways:

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

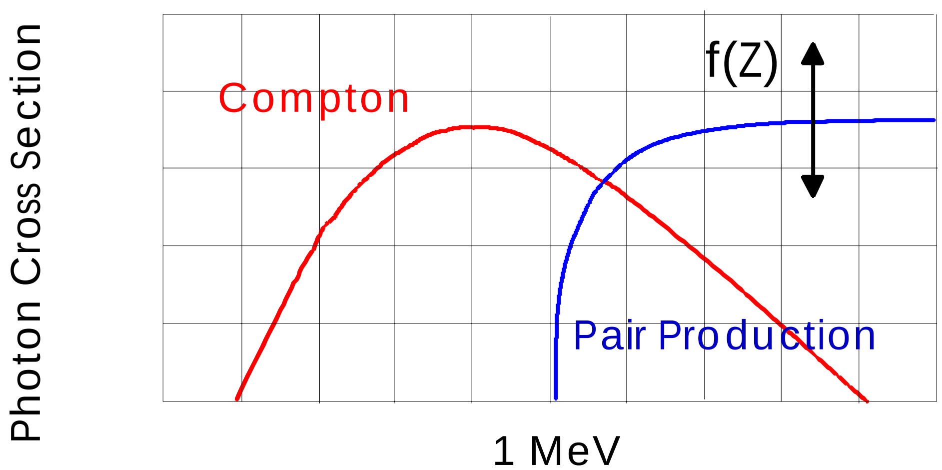
1)



2)



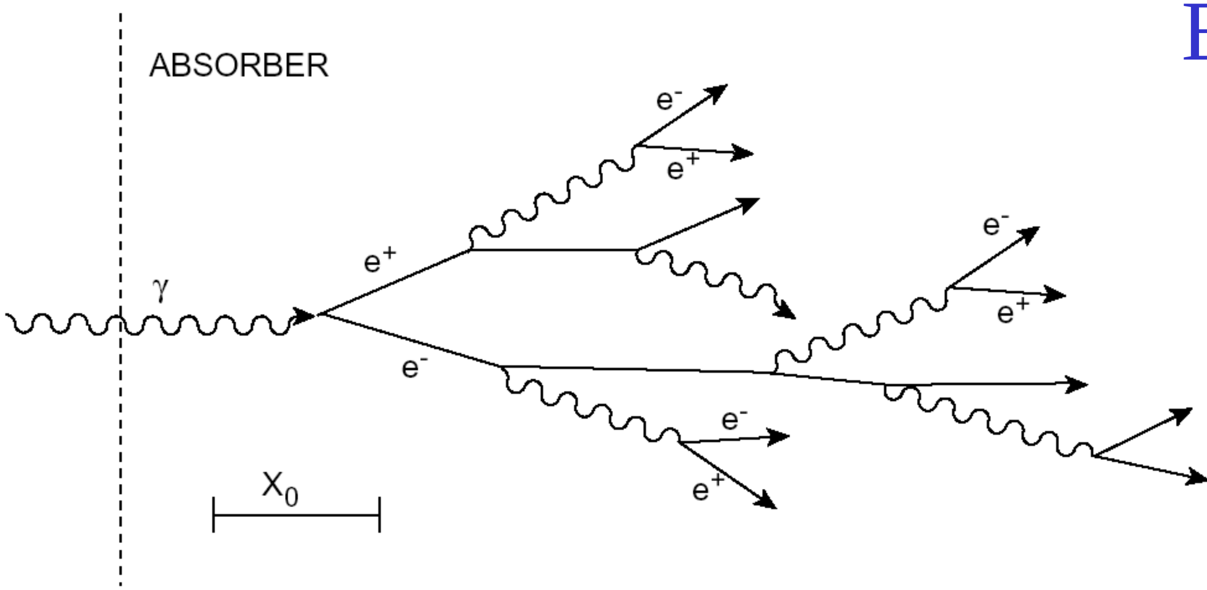
3) $\gamma + A \rightarrow A^* + e^-$



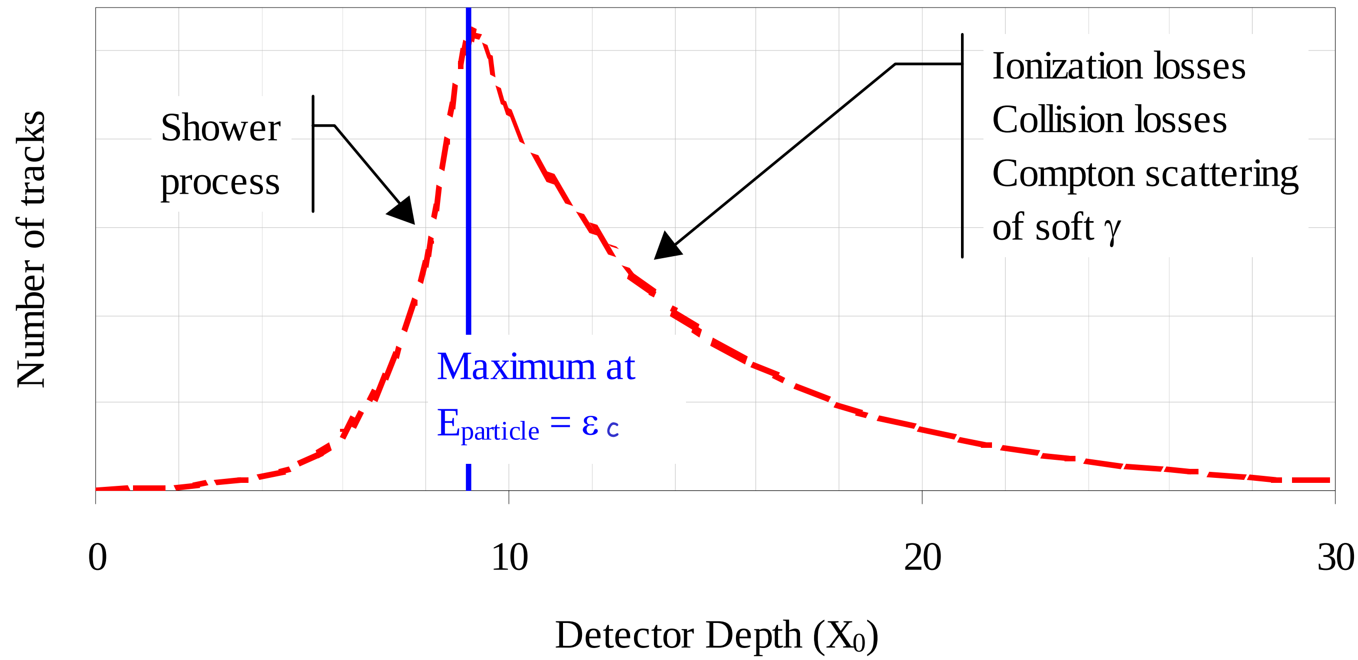
Mean free path for pair production $\gamma \rightarrow e^+e^-$ in a material is $9/7\ X_0$
… very similar to Bremss…

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

Electromagnetic Shower Development

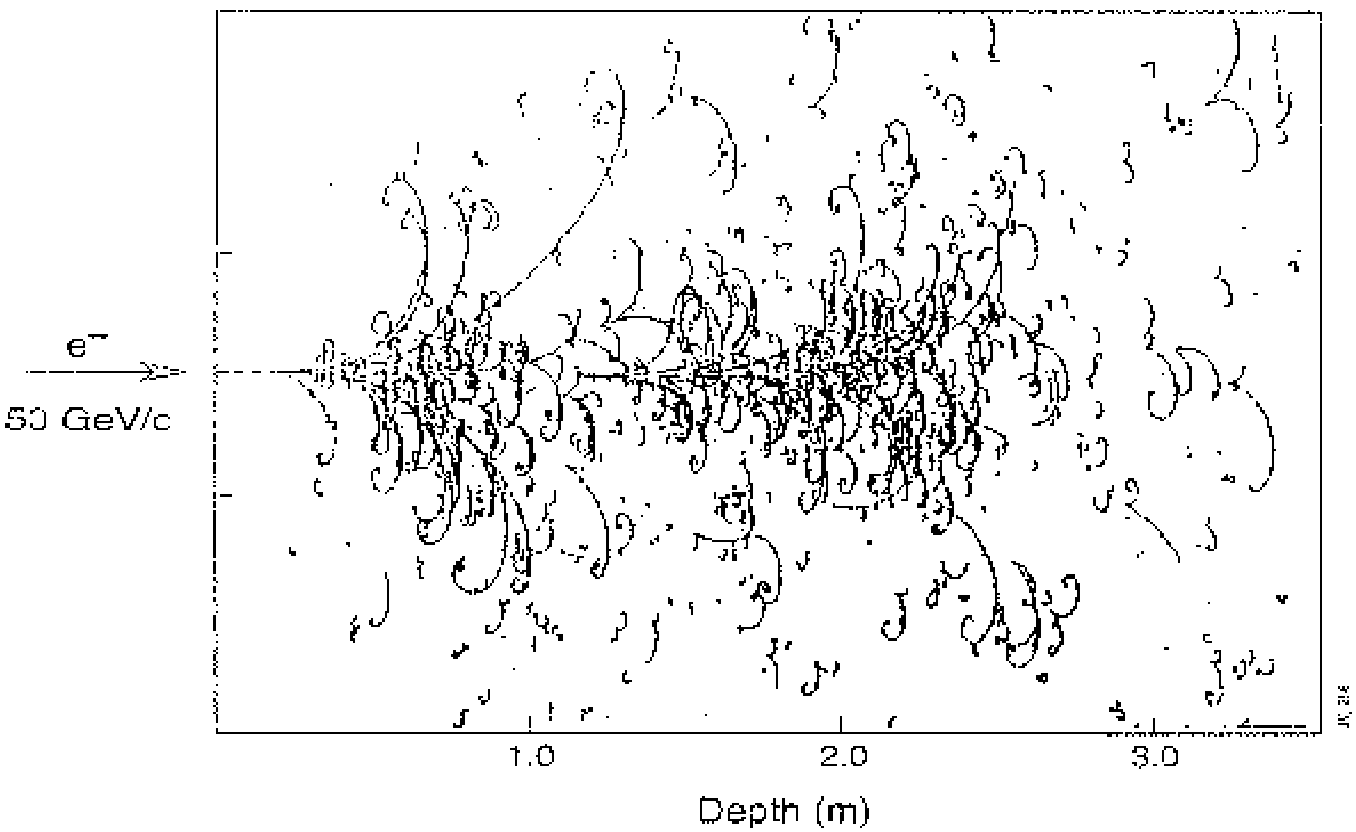


Shower maximum when shower particles on average have an energy equal to the critical energy



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



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Summary of an Electromagnetic Shower

- Bremsstrahlung and pair production ...
  - Shower deposits const energy in each radiation length
  - Each step the number of particles in the shower doubles
  - The energy per particle reduces by a factor of two
  - The emission angles are small so narrow shower develops
  - Shower width mainly comes from multiple scattering
- When the energy falls below the critical energy
  - Ionisation and collisions dominate the energy loss
  - Showers stops over a relatively short distance

Hadronic Showers

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

Define nuclear interaction length λ via $E(x) = E(0)\, e^{-x/\lambda}$ [$\lambda >> X_0$]

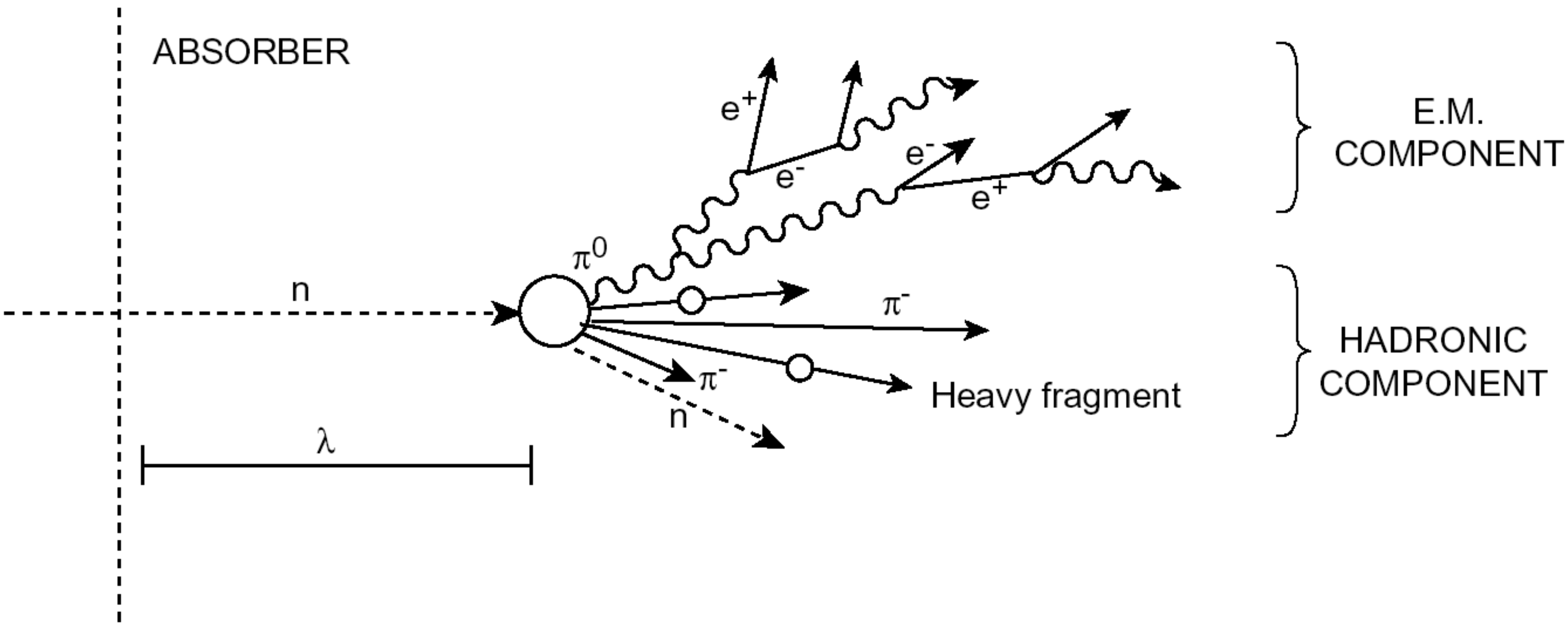
Roughly, **$\lambda \sim 35\ A^{1/3}$ g cm^{-2}**, quite long even for dense materials,
so **hadronic showers are longer and broader than EM showers**

Other difficulties compared with electromagnetic showers:

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

Development of Hadronic Showers

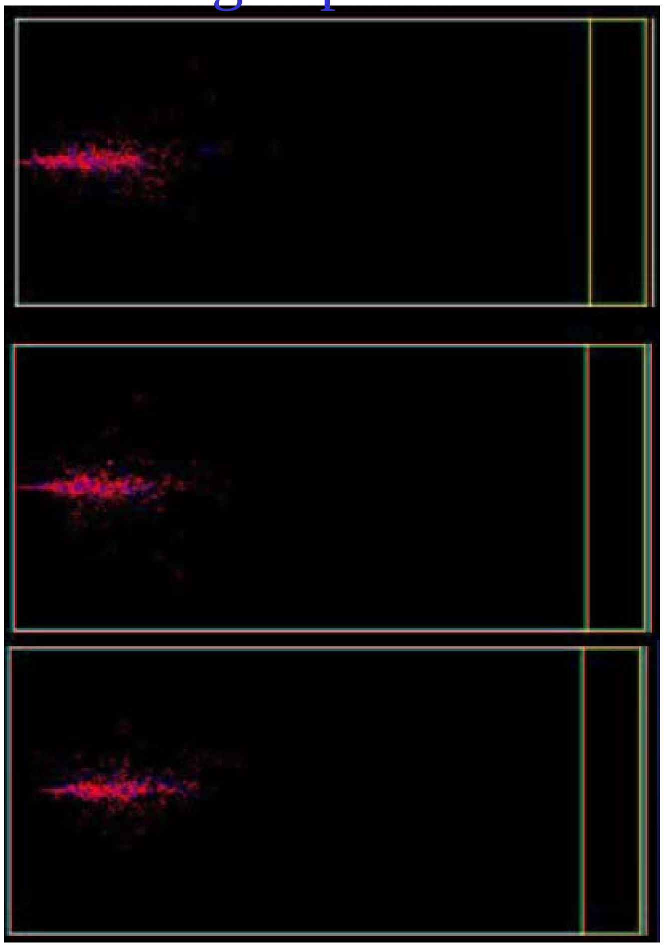
Nuclear interactions lead to large energy loss, but have long λ
($\lambda \sim 50$ cm for protons in lead)



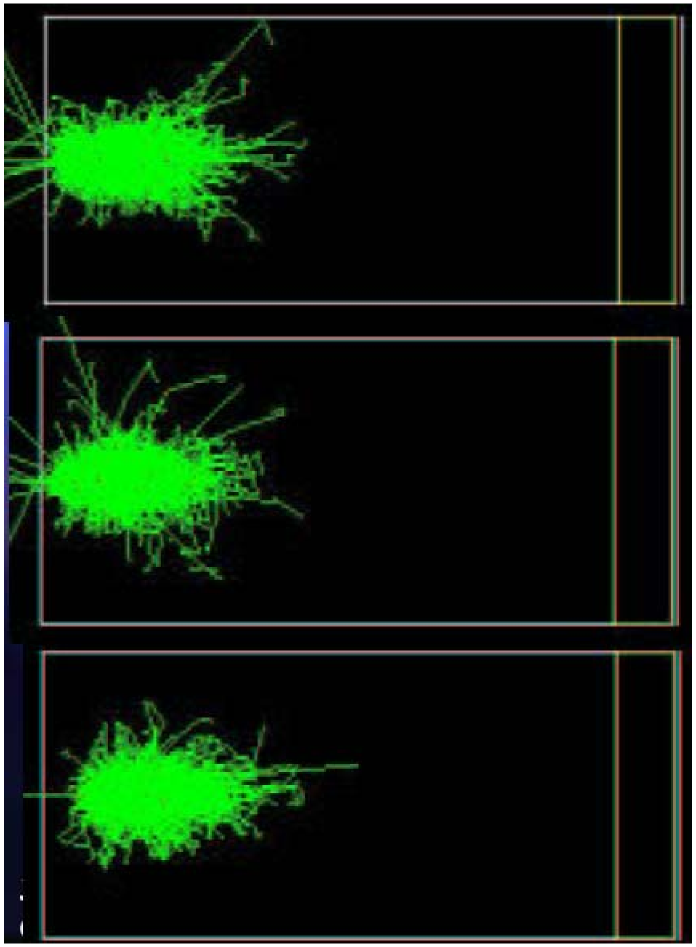
Breakdown of a Hadronic Shower

20 GeV hadronic showers in copper ….

Charged particles

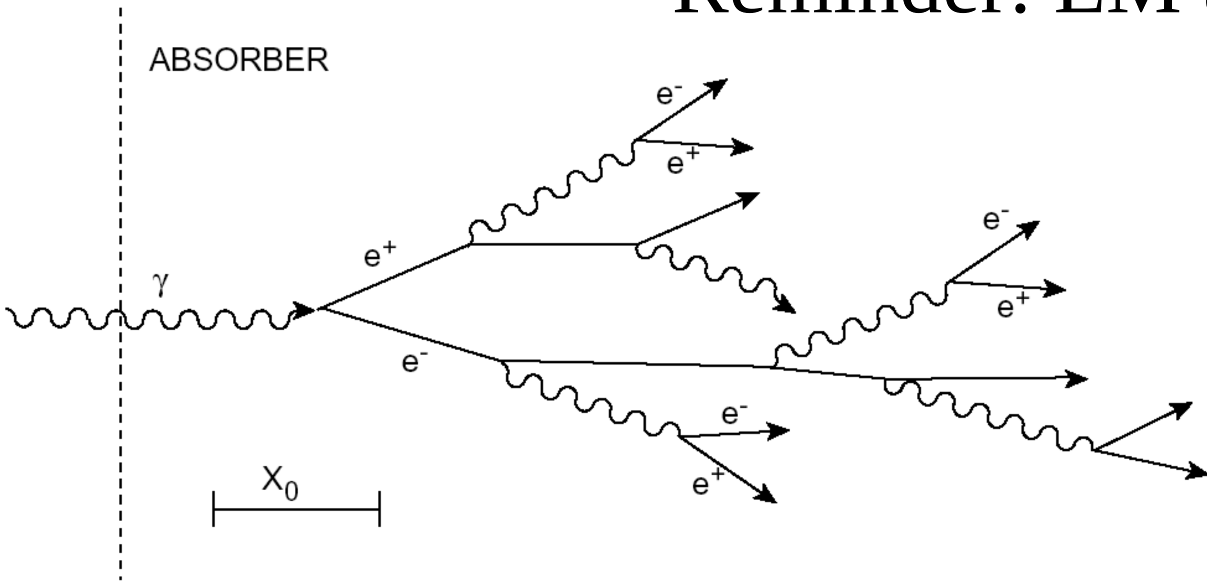


Full shower



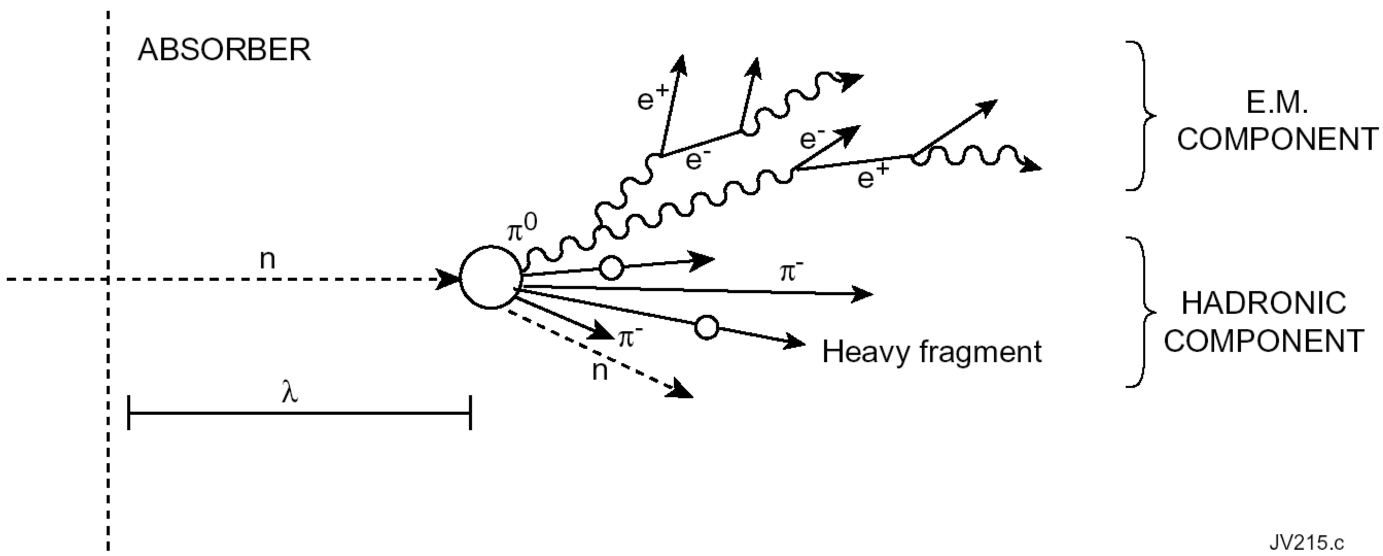
Large transverse component, especially in neutrals

Reminder: EM and HAD showers



Electromagnetic Shower

Hadronic Shower



... Now just have to detect and measure particles in shower!

Basics of Calorimeter Design

Calorimeters require:

A dense **ABSORBER** material in which to build shower
A **SAMPLER** as a means of measuring the shower contents / 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 scintilation from charged shower component
Used for all hadronic and many electromagnetic calorimeters

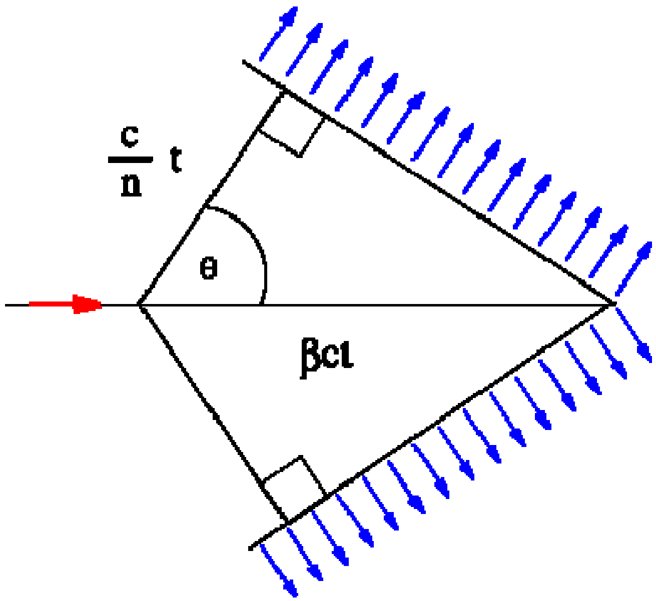
Homogeneous Calorimeters

Use special optical properties of crystals or glasses to generate detectable signal from electrons and photons in shower (scintillation light or Cerenkov radiation).

Aside: Cherenkov radiation

• Analogous to a supersonic shockwave.

• Charged particle with $v > c/\eta$ emits coherent radiation at an angle $\cos\theta = 1/\eta\beta$ to incident particle …. ring of photons seen in detector



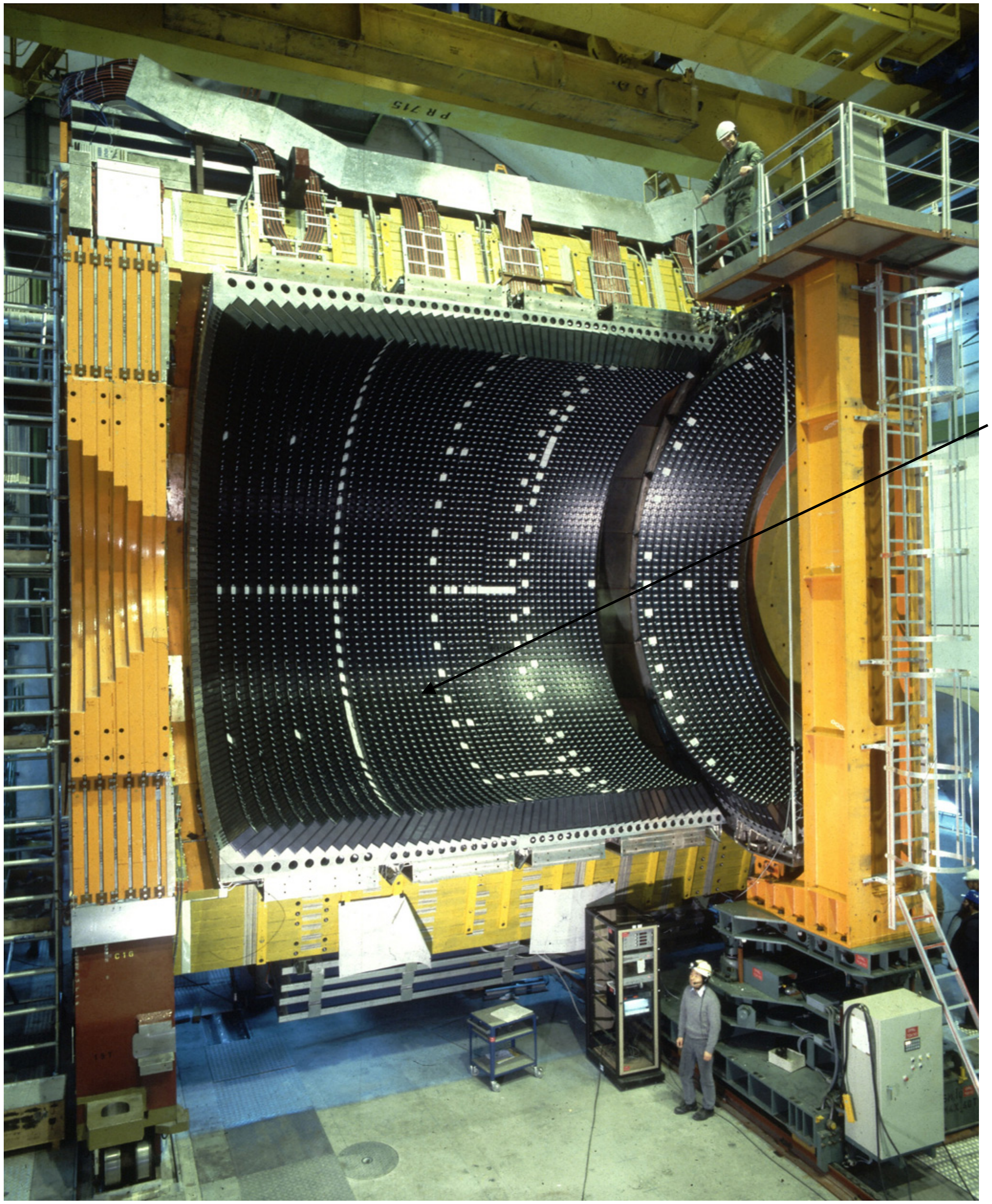
Application to Crystal Calorimeters:

• Electrons and positrons in electromagnetic shower emit Cerenkov radiation at optical wavelengths.

• Radiation collected in photomultiplier tubes

• Total light amplitude collected proportional to total energy deposited by incident e / γ

An Example Homogeneous Calorimeter

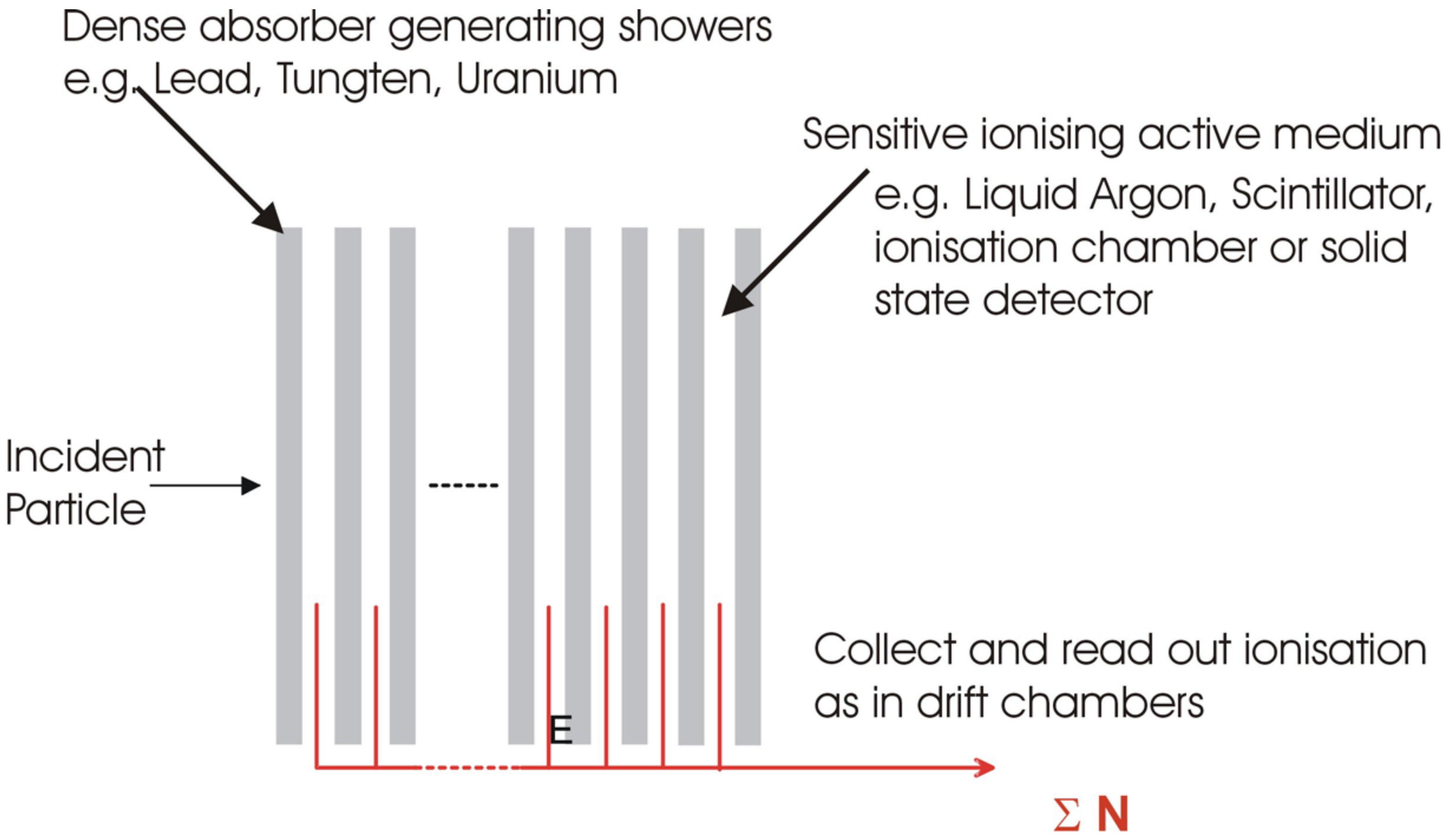


Individual lead glass blocks

- OPAL EM Calorimeter

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

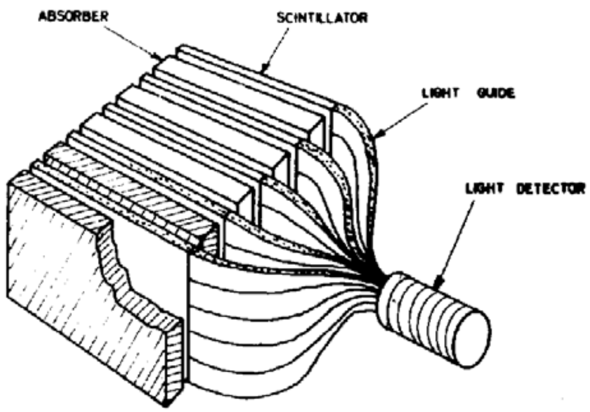
Sampling Calorimeters



- (Ionising) charged component of the shower (e+, e- …) sampled
- Can fill large and awkward volumes at acceptable cost
- Only a fraction of deposited energy is sampled

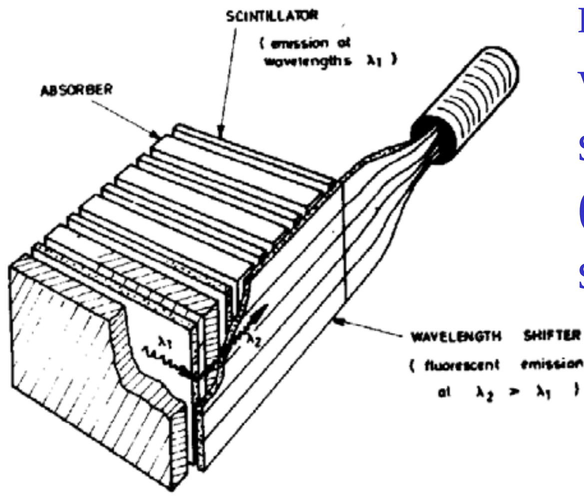
Some Example Sampling Calorimeter Designs

Scintillator readout



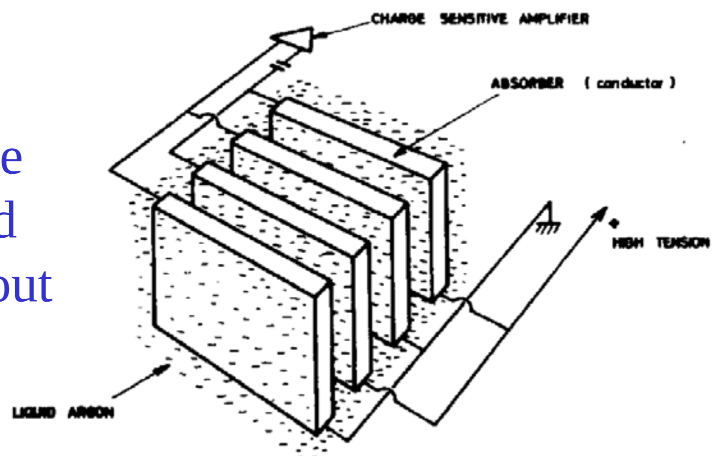
a)

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



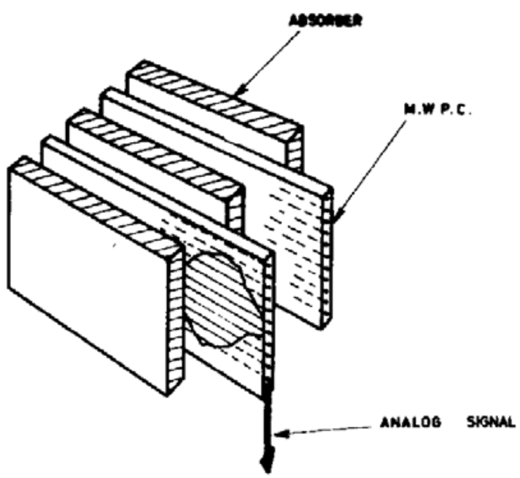
b)

Noble liquid readout



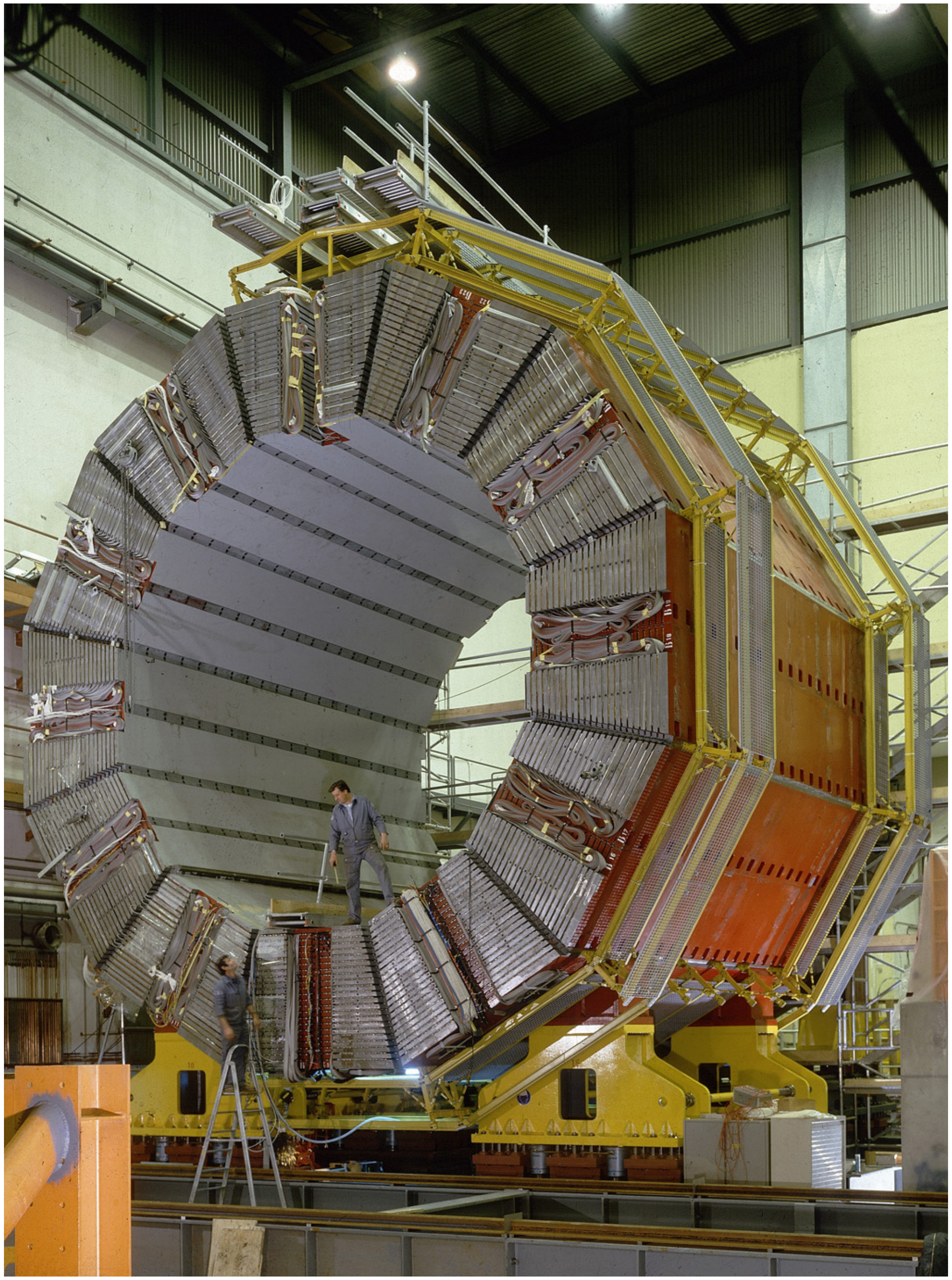
c)

Readout with gaseous detectors (MWPCs or streamer tubes)



d)

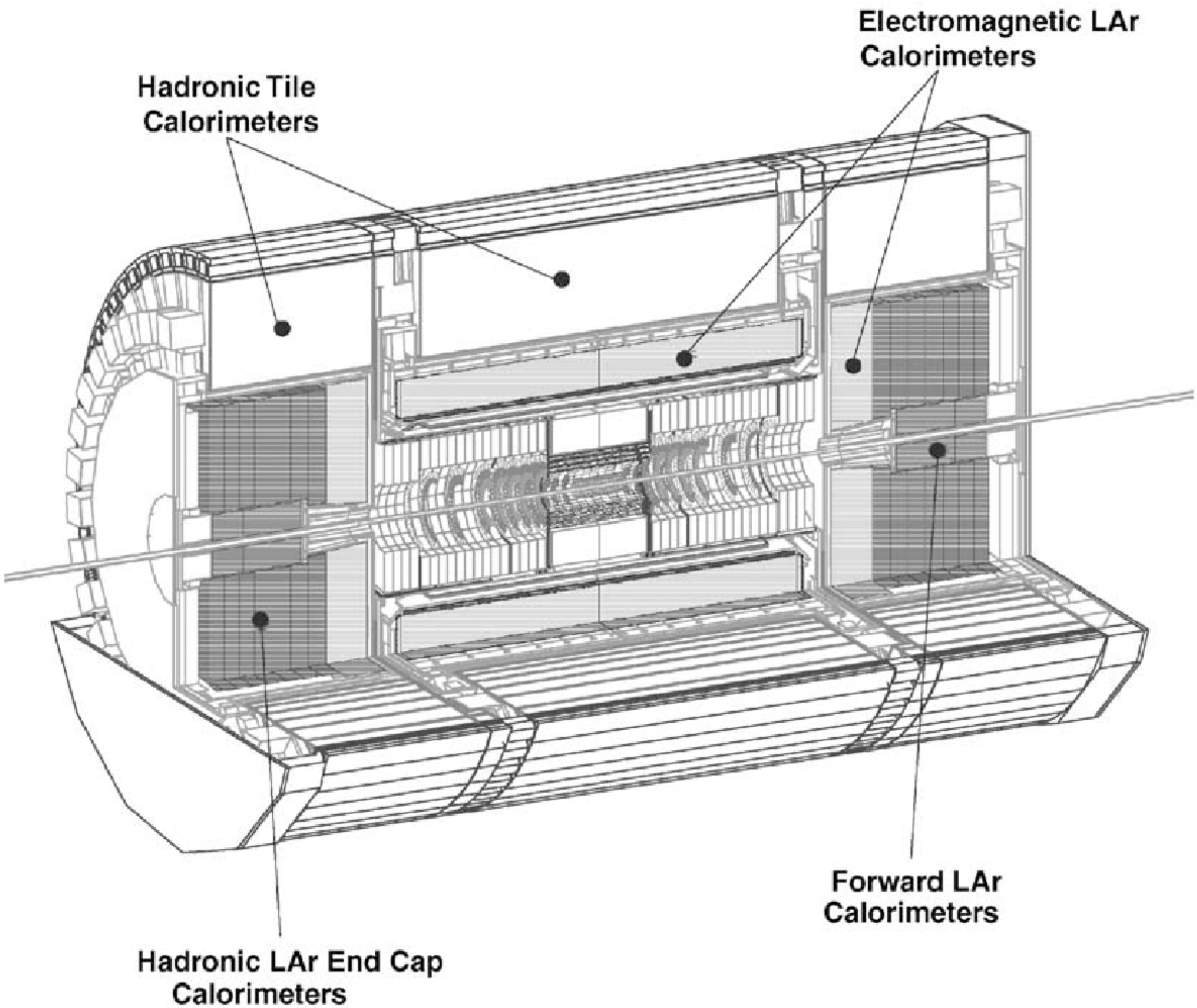
e.g. Hadronic Calorimeter at ALEPH



Iron return yoke of solenoid used as absorber material

Active material is limited streamer tubes (… see lecture on gaseous tracking chambers

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)

Calorimter Resolution

Resolution of a Calorimter usually Considered in 3 parts:

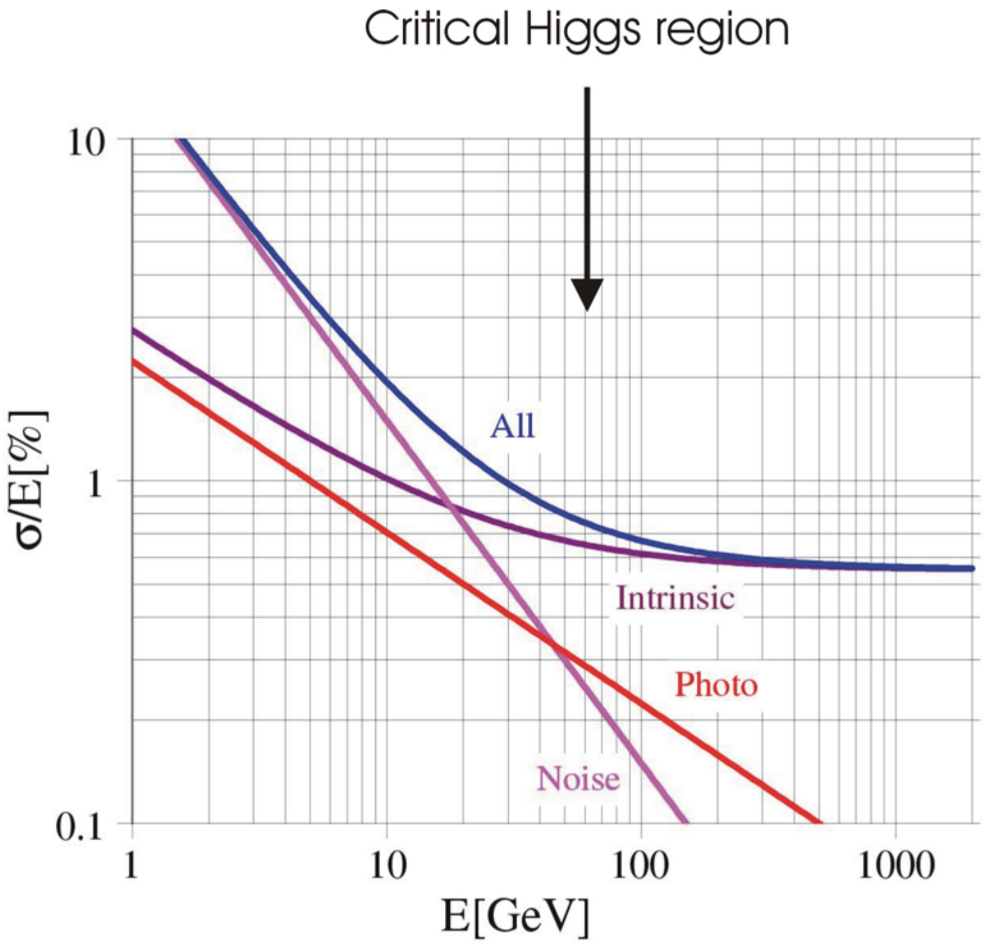
1. $\sigma(E) \propto \sqrt{E}$ ‘counting error’ due to statistical fluctuations in showering / sampling
2. $\sigma(E) \propto const$ Energy independent error due to electronic noise, pile-up of other events at LHC ...
3. $\sigma(E) \propto E$ Losses due to leakage or dead material, systematics such as miscalibration

Usually quoted as a fractional error ($\bigoplus$ means ‘add in quadrature’)

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

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 high E, $\sigma(E)/E \sim 1/E^{1/2}$, dominated by `intrinsic' statistical sampling error

c.f. trackers, $\sigma(p_t)/p_t \ \alpha \ p_t$

NB! Calorimeter resolution improves with increasing energy
Tracking resolution deteriorates with increasing energy
… the two types of detector are often complementary!