UNIVERSITY OF LIVERPOOL

Particle Detection Techniques in HEP

Lecture 4: Calorimetry

Post-graduate lecture series

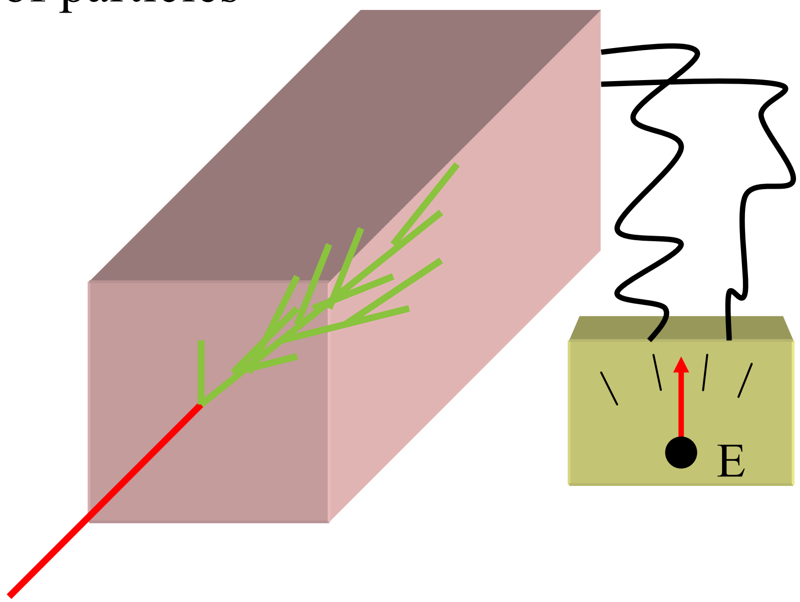
Joost Vossebeld

Lecture 4 “Calorimetry”

- Introduction
- Energy loss by electrons and photons
- The electro-magnetic shower
- The Rossi model
- Photo emission by particles in matter
- Electro-magnetic calorimeters
- Showering of hadrons
- Hadronic calorimeters

Calorimetry

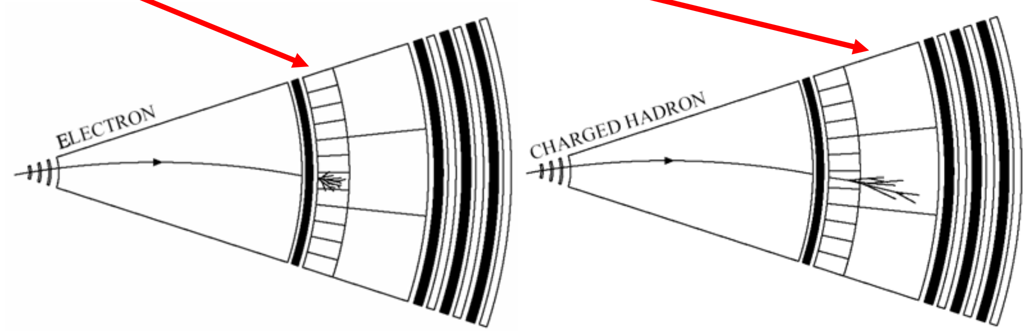
"Measurement of the energy by ***total absorption*** of particles"



The energy of both charged and neutral particles can be measured!

To stop high energy particles (over a limited distance), calorimeters are typically built of high density materials.

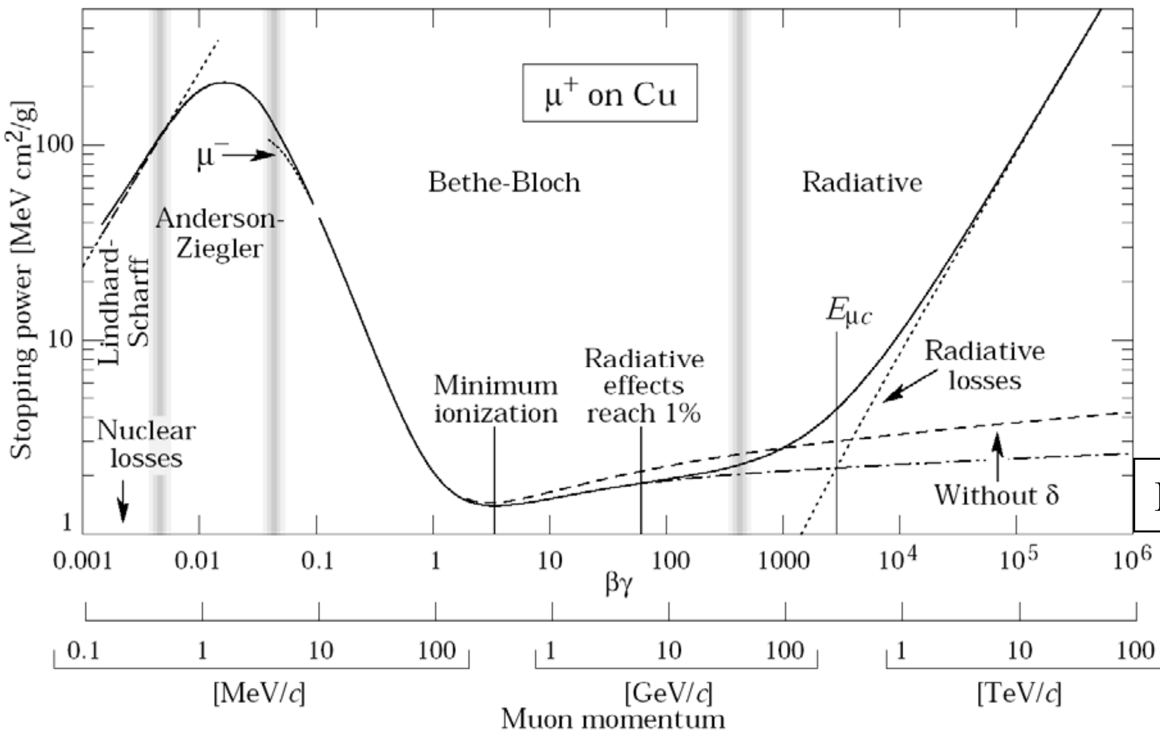
In HEP we use electro-magnetic and hadronic calorimeters



To see why we must discuss:

- Energy loss by electrons and photons (e.m. showers)
- Energy loss by hadrons (hadronic showers)

Reminder: Energy loss by charged particles governed by Bethe-Bloch equation (ionisation)



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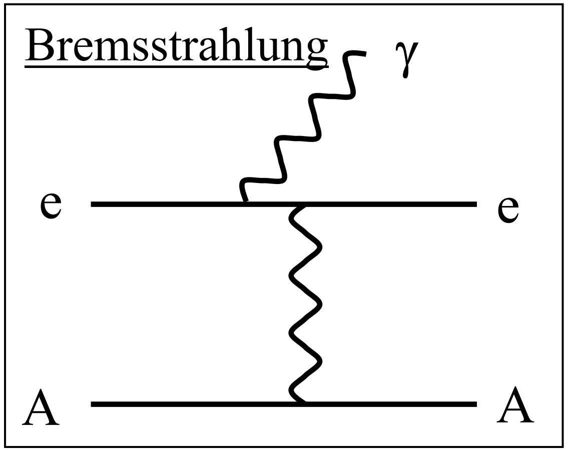
At very low energy ionisation impossible. Only interactions with nucleus.

For most particles ionisation dominates from a few MeV up to TeV-scale.

Above that Bremsstrahlung due to nuclear electric field dominates.

Electrons (very low mass) are an exception!

Bremsstrahlung:



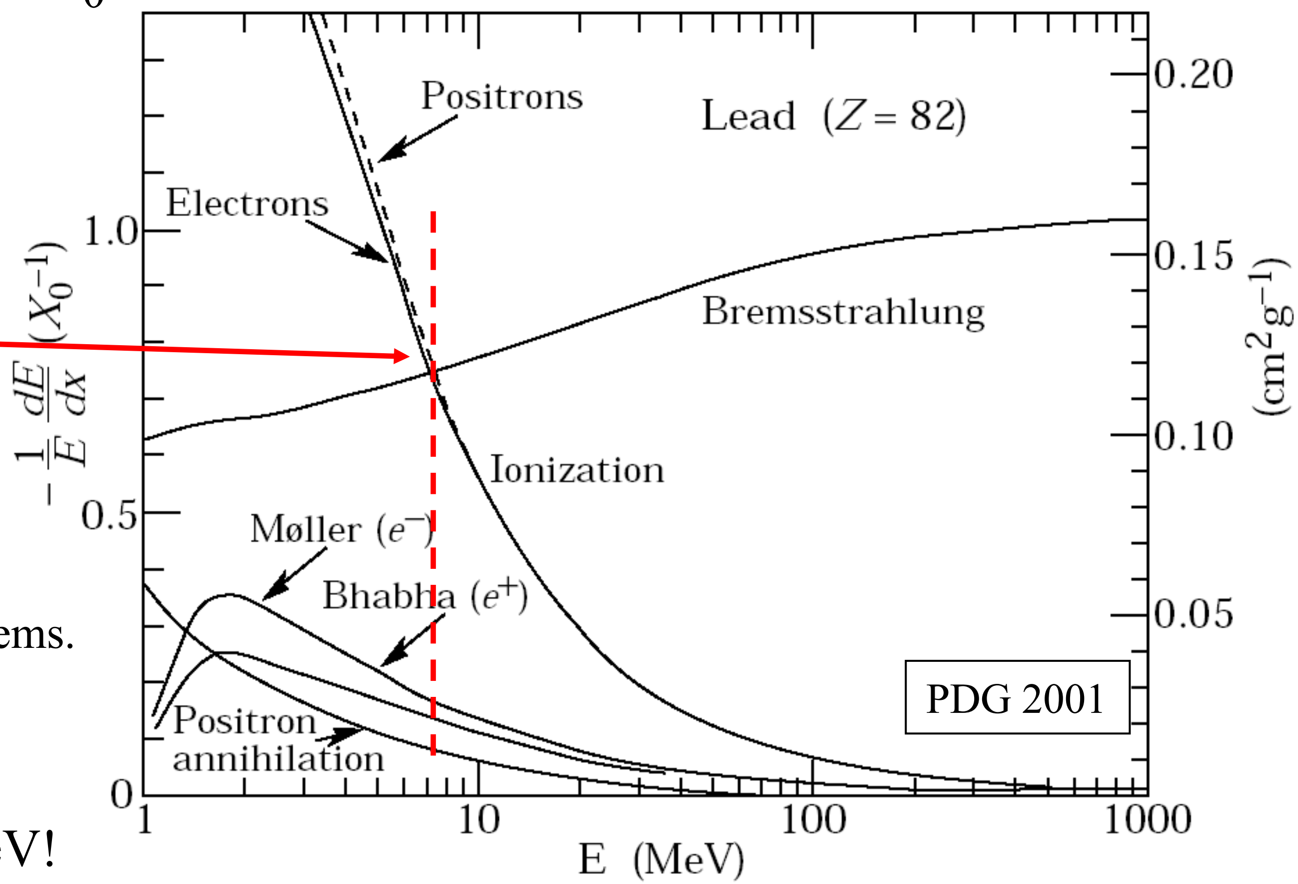
Highly relativistic charged particles loose energy by radiating photons due to the ***E***-field of nuclei.

$$-\frac{\mathrm{d}E}{\mathrm{d}x} \approx 4\alpha \mathrm{N_A} \frac{Z^2}{A} z^2 \frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} E \ln\frac{183}{Z^{1/3}}$$

As before: $\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{1}{\rho}\frac{\Delta E}{\Delta x}$

This process dominates above the critical energy: $\boldsymbol{E}_\mathbf{c}$

$$\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{Ion.}} = \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)_{\mathrm{Brems.}}$$



For electrons: $\boldsymbol{E}_\mathbf{c}$ = 5-20 MeV!

Bremsstrahlung dominates in the most of the energy range relevant to HEP.

The Radiation length $\boldsymbol{X_0}$:

Expression for Bremsstrahlung (for electrons):

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 4\alpha \mathrm{N}_A \frac{Z^2}{A} \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2} E \ln\frac{183}{Z^{1/3}}$$

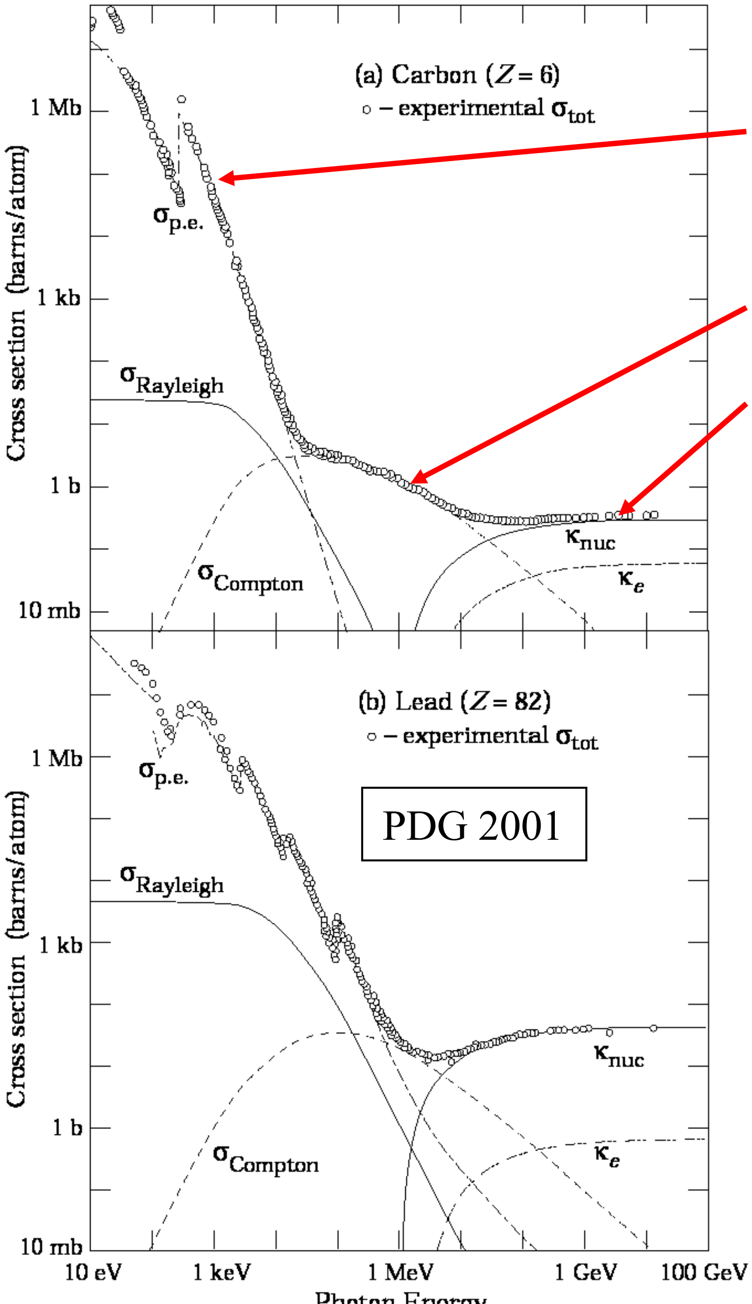
or $\quad -\dfrac{\mathrm{d}E}{\mathrm{d}x} = \dfrac{E}{X_0}$ $\quad$ with $\quad X_0 = \left(4\alpha \mathrm{N}_A \dfrac{Z^2}{A} \dfrac{1}{4\pi\varepsilon_0} \dfrac{e^2}{m_e c^2} \ln\dfrac{183}{Z^{1/3}}\right)^{-1}$ (g/cm^2)

How to interpret this $\boldsymbol{X_0}$?

$$E(x) = E_0 \exp\left(-\frac{x}{X_0}\right)$$

After traversing $\boldsymbol{X_0}$ of material the average electron has lost all but ***1/e*** of its energy to photon radiation.

<u>**Radiation length**</u> ($\boldsymbol{X_0}$) depends only on the type of material.

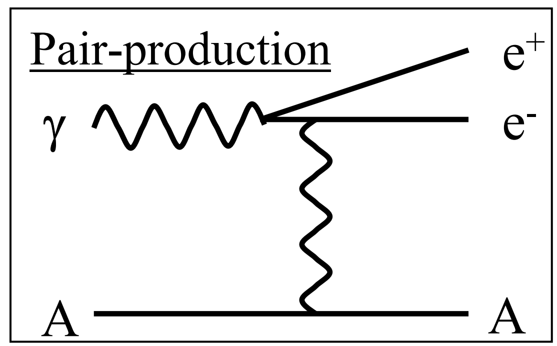


Energy loss by photon:

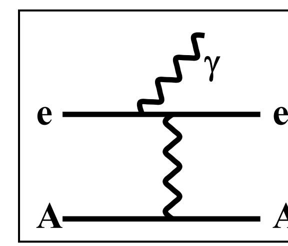
Photo-electric effect: **A**$\boldsymbol{\gamma} \Rightarrow$ **A**$^+$**e** (***E*** <10-100 keV)
(discontinuities due to ionisation thresholds)

Compton scattering: **e** $\boldsymbol{\gamma}$ **A**$\Rightarrow$ **e** $\boldsymbol{\gamma}$**A**

Pair-production: $\boldsymbol{\gamma}$ **A**$\Rightarrow$ **e**$^+$ **e**$^-$**A** (***E*** >1-10 MeV)
(due to ***E***-field nuclei)



(Topologically similar to Bremsstrahlung!)



$$\sigma_{\text{pair}} \approx 4\alpha\, Z^2 \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2} \frac{7}{9} \ln \frac{183}{Z^{1/3}}$$

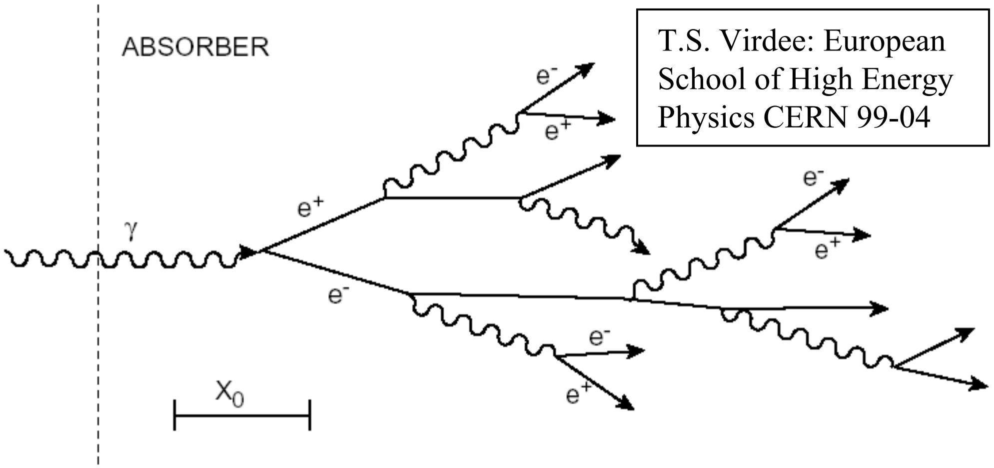
$$\approx \frac{7}{9} \frac{A}{\mathrm{N}_A} \frac{1}{X_0} \ (\mathrm{cm}^2/\mathrm{atom})$$

$$\approx \frac{7}{9} \frac{1}{X_0} \ (\mathrm{cm}^2/\mathrm{g})$$

Mean-free-path for photons is **9/7***$\boldsymbol{X_0}$ ($\propto$ **1/σ**), very similar to that for electrons!

The electro-magnetic shower

Electrons or photons in a thick absorber generate an **electro-magnetic shower** by subsequent Bremsstrahlung and pair production processes.



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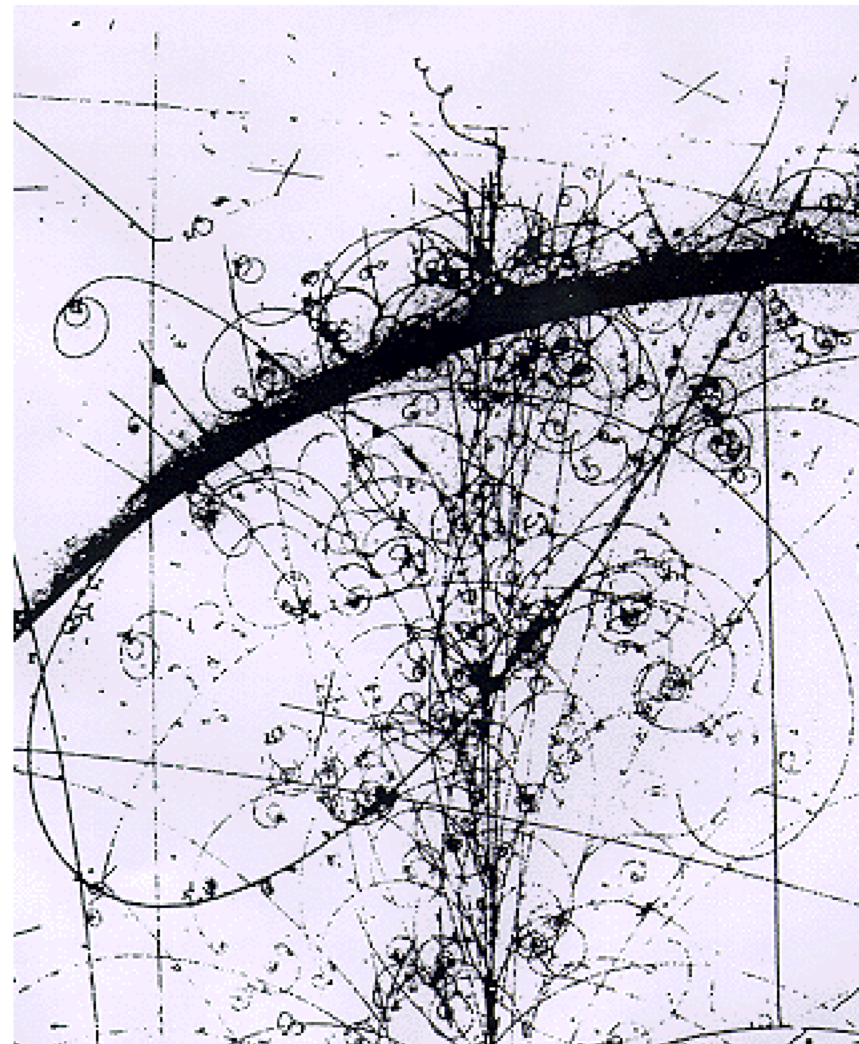
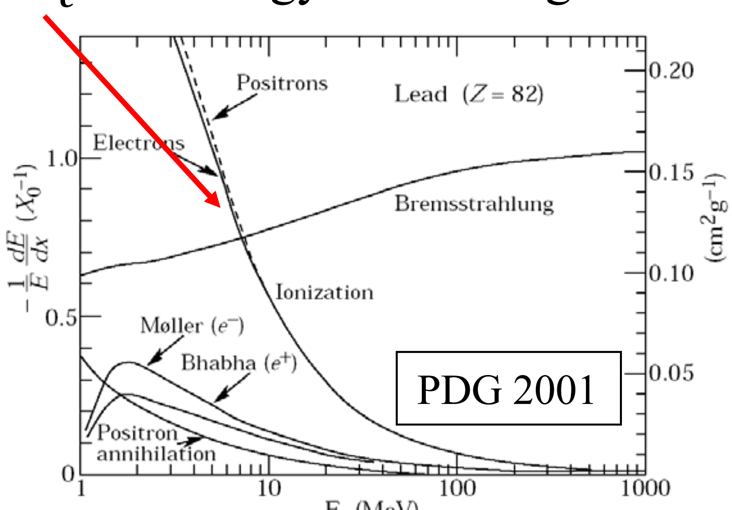
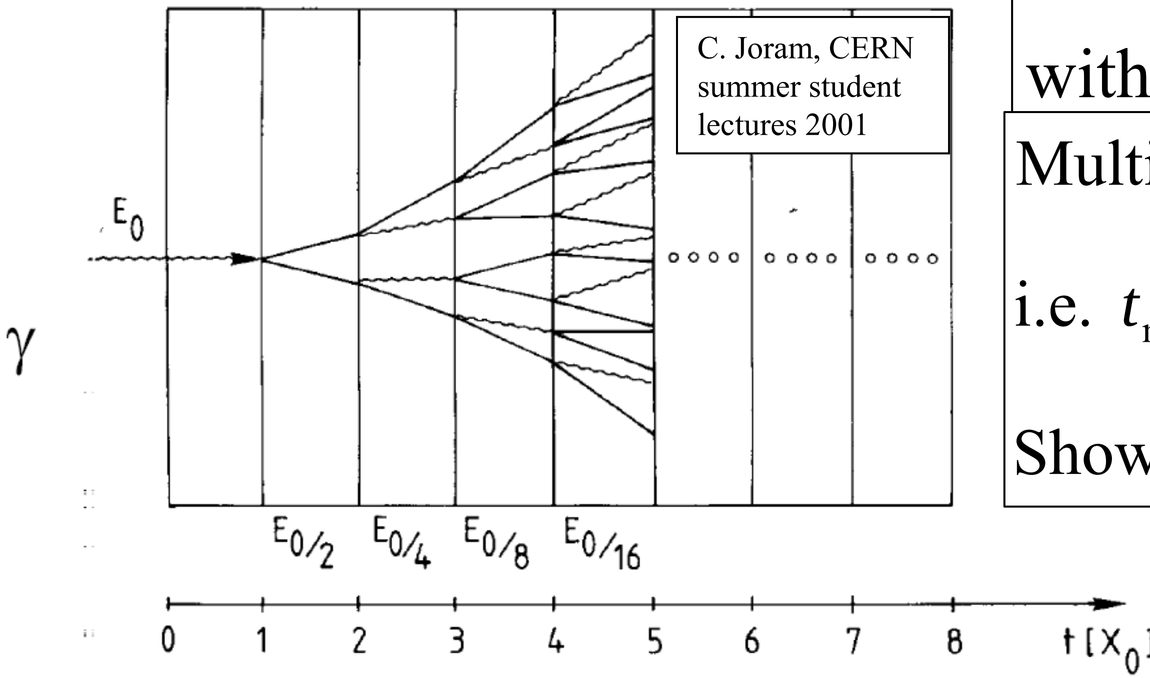


Shower stops when $\boldsymbol{E<E_c}$!

Below $\boldsymbol{E_c}$ fast energy loss through ionisation.



The Rossi model:



After t steps : 2^t particles with energy $E_0/2^t$.

Multiplication ends : $E_0/2^t = E_c$

i.e. $t_{\max} = \dfrac{1}{\ln(2)} \ln\left(E_0/E_c\right)$

Shower depth $\propto \ln(E_0)$

$$N_{\text{total}} = \sum_{t=0}^{t=t_{\max}} 2^t \approx 2\frac{E_0}{E_c}$$

$$N_{\text{charged}} = \frac{4}{3}\frac{E_0}{E_c}$$

$$E_0 \propto N_{\text{charged}}$$

Rossi model: <u>regular</u> Bremsstrahlung and pair-production with <u>equal energy splitting</u>.

<u>Resolution :</u> $\dfrac{\sigma(E)}{E} \propto \dfrac{\sqrt{N_{\text{charged}}}}{N_{\text{charged}}} = \dfrac{1}{\sqrt{N_{\text{charged}}}} \propto \dfrac{1}{\sqrt{E}}$

In more detail : $\dfrac{\sigma(E)}{E} = \dfrac{a}{\sqrt{E}} \oplus b \oplus \dfrac{c}{E}$.

a: stochastic term

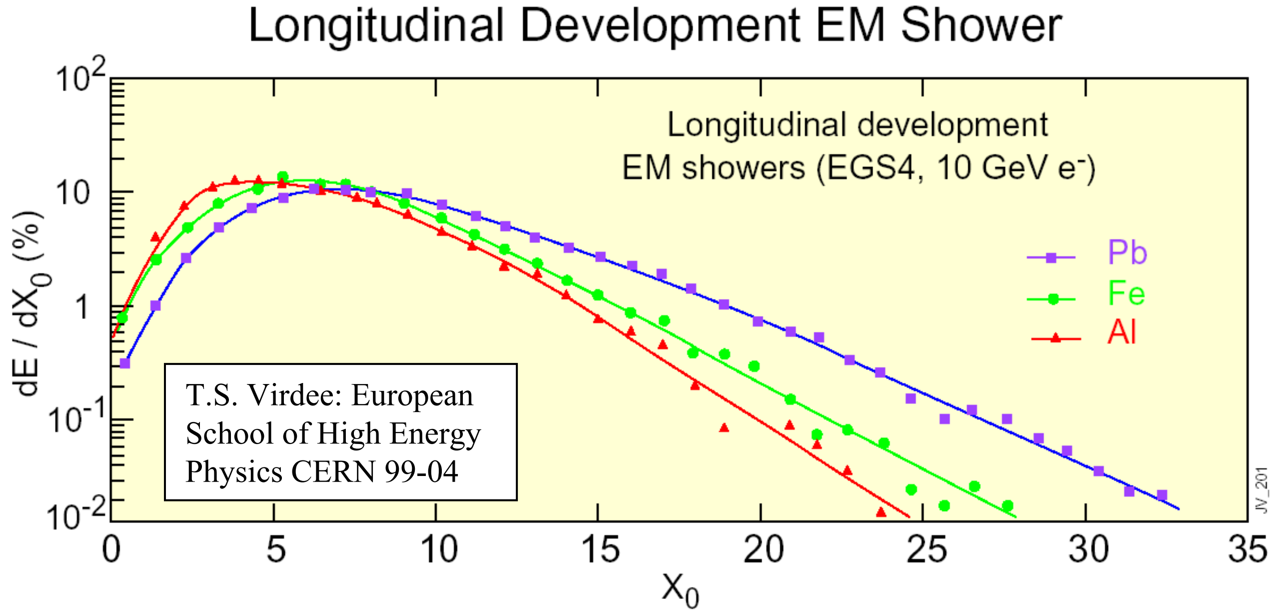
b: constant term (inhomogenities, cell-to-cell calibration,..)

c: noise term (electronic noise)

Shower depth

Depth in radiation lengths (X_0) is the relevant variable!

Shower maximum roughly when $E \approx E_c$. (long tail)



Medium	Density ρ [g/cm³]	Radiation length X_0 [cm] (really X_0/ρ)
Copper (Cu)	9.0	1.43
Lead (Pb) (ATLAS)	11.4	0.56
Uranium (U) (ZEUS)	19.0	0.32
Plastic scintillator	~1.0	~43
Liquid Argon	1.4	14
Liquid Xenon	3.1	2.8
Lead-glass (OPAL)	3.86	2.54
CsI (BaBar)	4.51	1.9
BGO (L3)	7.13	1.1
$PbWO^4$ (CMS)	8.3	0.9

Typically for ~99% containment a calorimeter thickness of about 20 X_0 is needed:

- **28.6 cm of copper**
- **11.2 cm of lead**
- **6.4 cm of uranium**
- **~8.6 m of plastic-scintillator!!**
- **51 cm of lead-glass**
- **18 cm of $PbWO^4$**

2 options for (limited size) E.M. calorimeter:
Homogeneous: dense detector material
Sampling: dense absorber + light detector mat.

Signal detection in calorimeters:

<u>Rossi model</u>: Energy of a particle can be measured from the total number of charged particles in a the shower! How can we measure this?

- Using ionisation detection (as in gaseous tracking detectors)
  - high segmentation achievable (via layout of electrodes)
  - low cost/space per channel

  e.g. Liquid Argon calorimeter: Ionisation in (cryogenic) liquid Argon. Charge collection using (for example) parallel plate chambers.

  (No need to have low density material as in gaseous trackers!)

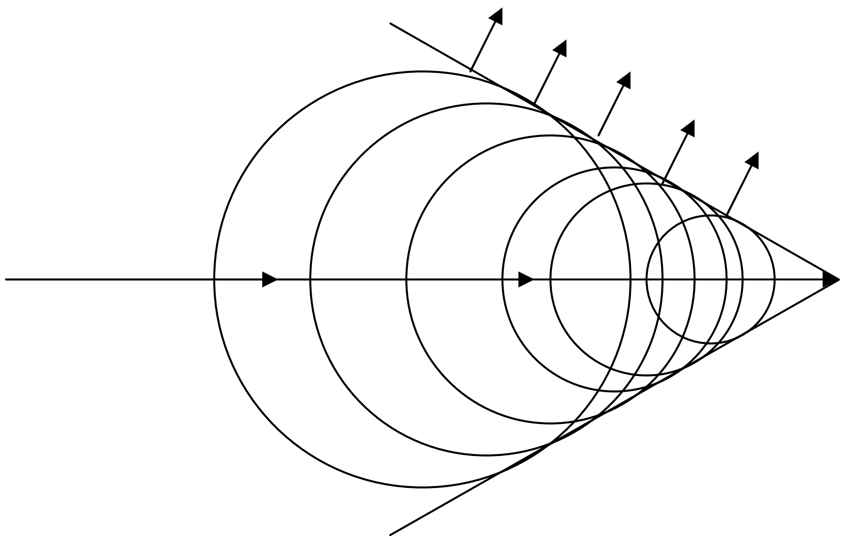
- By detection of photons from Scintillation or Cherenkov radiation:
  - much used in calorimetry
  - need photo detectors:
    - photo-multiplier tubes (sensitive, but bulky and expensive)
    - Photo-diodes
  - detector very robust (no electronics in detector itself)

Photon emission by particles in matter

- Cherenkov radiation

  Coherent light emission by a charged particle travelling faster than the speed of light in the material it is travelling in.

  Typically using a heavy transparent material (e.g Lead-glass)

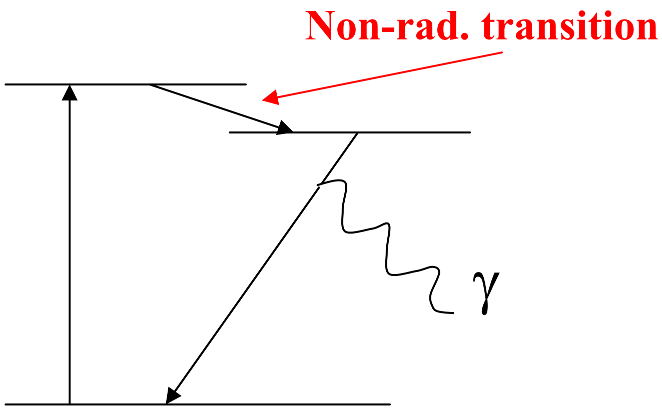


- Scintillation:

  Photo emission from atoms/molecules excited to a higher state by a charged particle. (different mechanisms, … next slide)

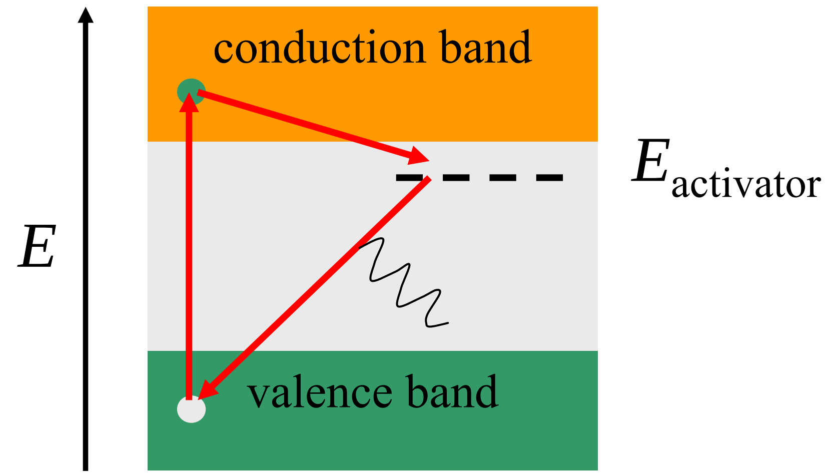
- Fluorescence:

  Photo emission from atoms/molecules excited to higher state by a (shorter wavelength) photon.



Different scintillation materials/mechanisms:

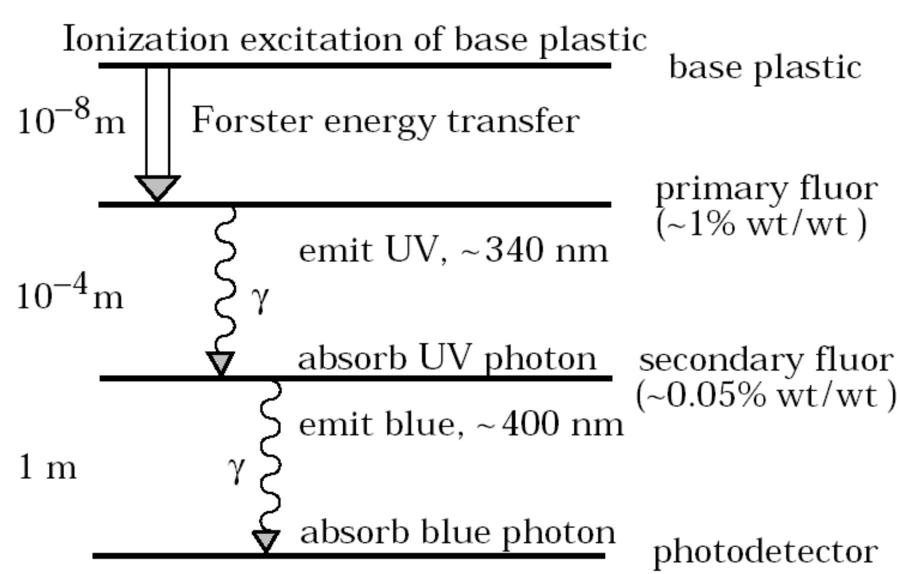
<u>Crystals</u>: e.g. NaI, CsI, $PbWO_4$ ..
High density and transparent!
Excitation of electrons into conduction band.
Doped with an activator (e.g. Thallium)



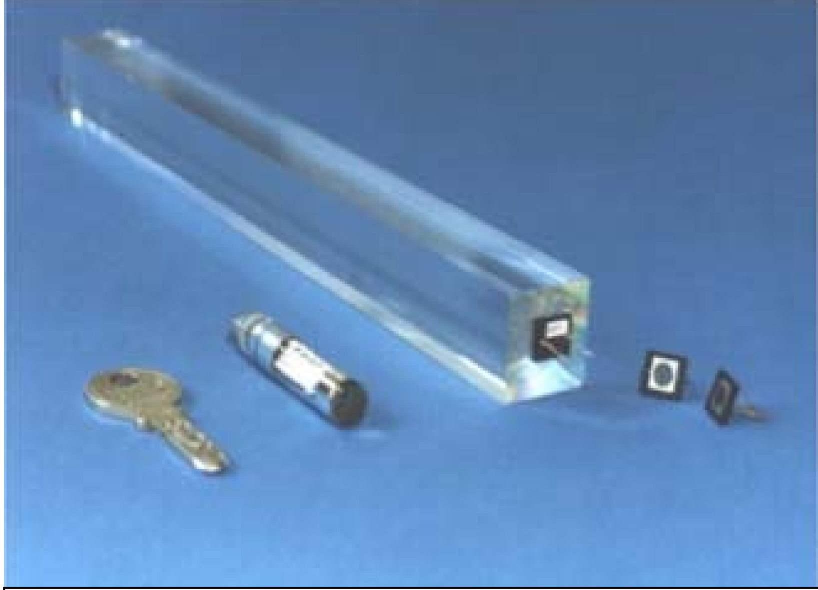
<u>Organic scintillators</u>: liquid or plastic
e.g. polystyrene (doped with "fluors")
Molecular excitation
Light emission in 3 steps:

1 scintillation in base material (UV)
2 primary fluorescence in UV
3 secondary fluorescence in Blue

Low density materials must be combined with a high density absorber material. (sampling calorimeter)



Homogeneous calorimeters



Detector = Absorber

Typically a high density transparent material in which scintillation or Cherenkov radiation produces photons

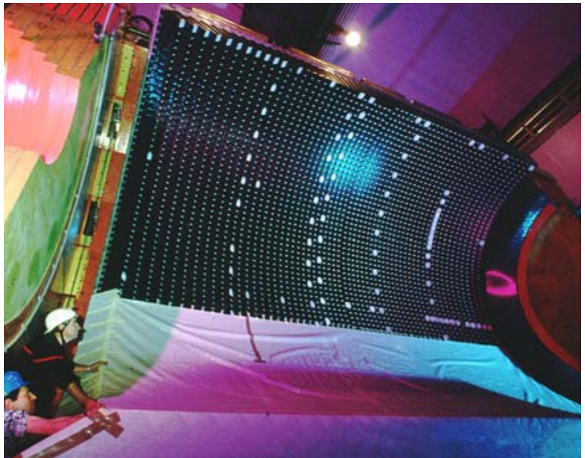
- Very good energy resolution
- Limited spatial resolution, depending on crystal size.

  (no longitudinal segmentation possible)

CMS ECAL: 80,000 $PbWO_4$ crystals

Avalanche photodiodes measure scintillation light

$$\frac{\sigma(E)}{E} \approx \frac{2.7\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.55\%$$



OPAL ECAL: ~10000 Lead-glass blocks

Photo-multiplier tubes measure the Cherenkov light

$$\frac{\sigma(E)}{E} \approx \frac{6\%}{\sqrt{E}} \oplus 0.2\%$$

Sampling calorimeters

Separate detector (active) and absorber (inactive) material

("Sample" parts of the shower.)

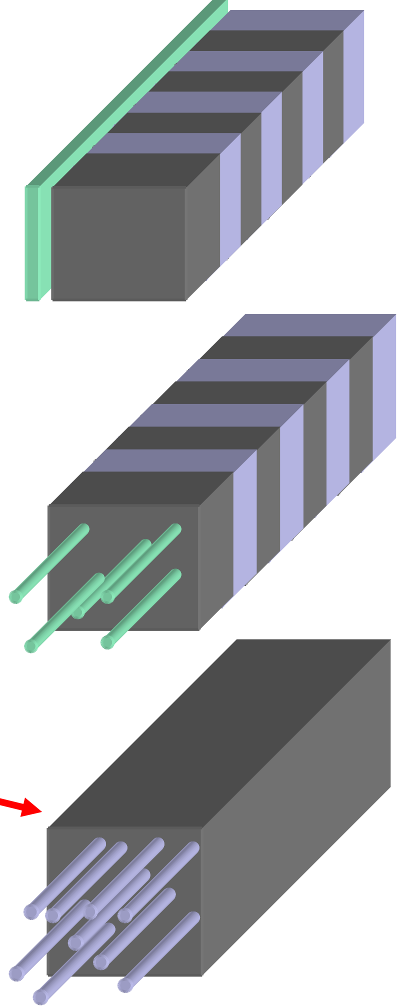
<u>Absorber material:</u> lead/tungsten/uranium/copper/..

<u>Detector material:</u>

- plastic scintillator plates or fibres:
  - **Sandwich**
  - **Shaslik**
  - **Spaghetti (no need to build cells!)**

  Light is guided to photo detector via
  wave-length shifting (and clear) fibres/rods/..
- Cryogenic liquid noble "gases" (next page)
  - **Liquid Krypton, Argon, Xenon, ..**

  charge collection on electrodes.
  Intrinsically radiation tolerant as liquid can be circulated



In general best resolution is obtained when there are many "samplings" and relatively much active material and less absorber material.

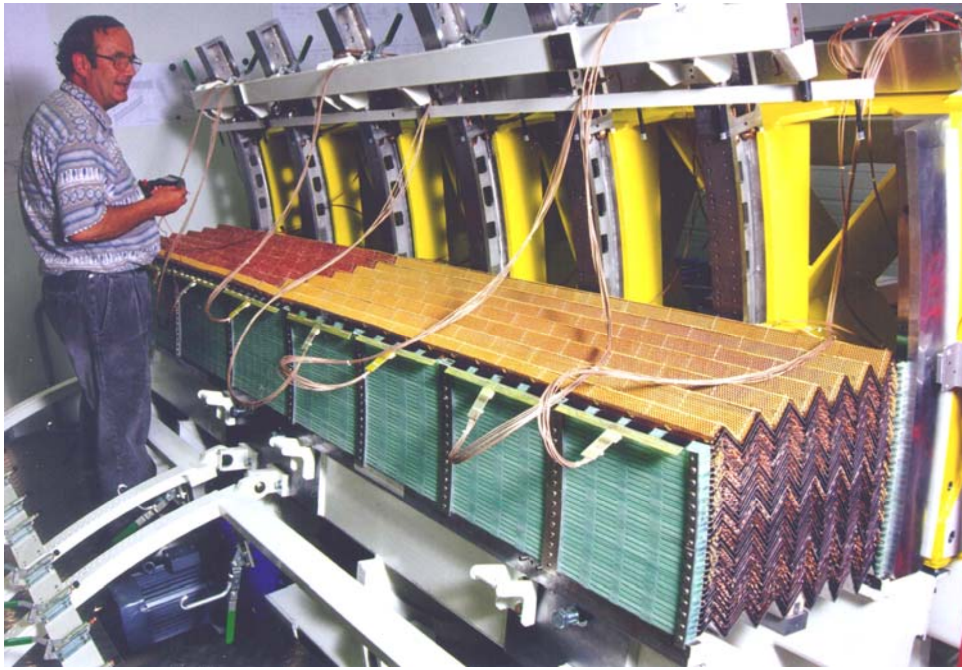
Overall poorer resolution than homogeneous calorimeters.

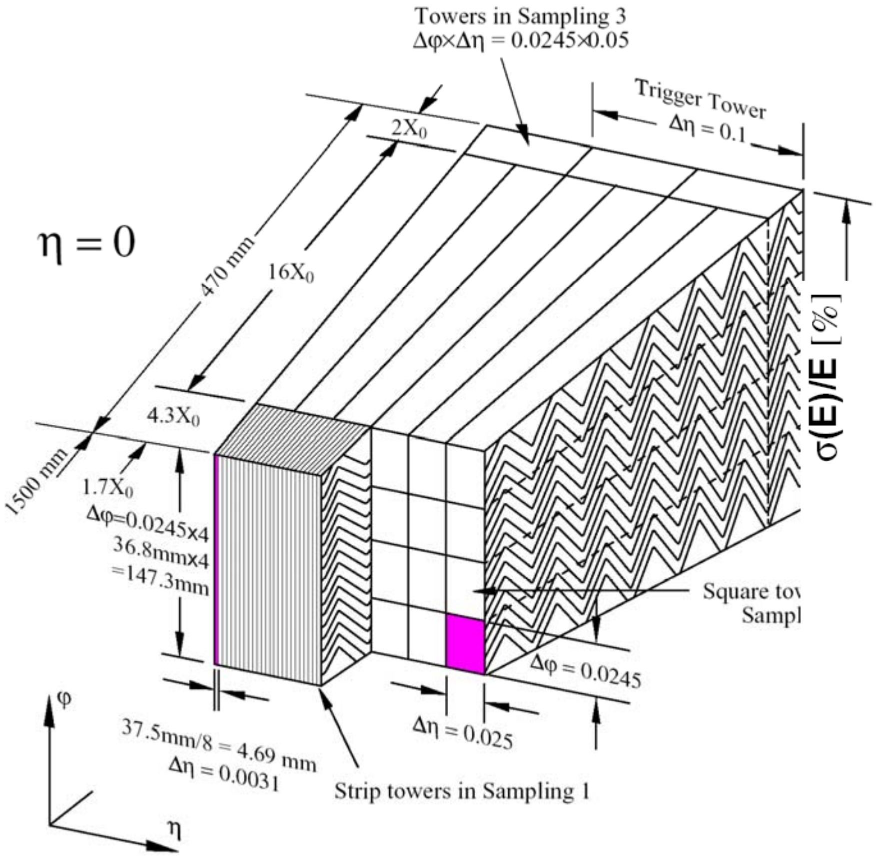
Example: ATLAS Electro-magnetic barrel calorimeter

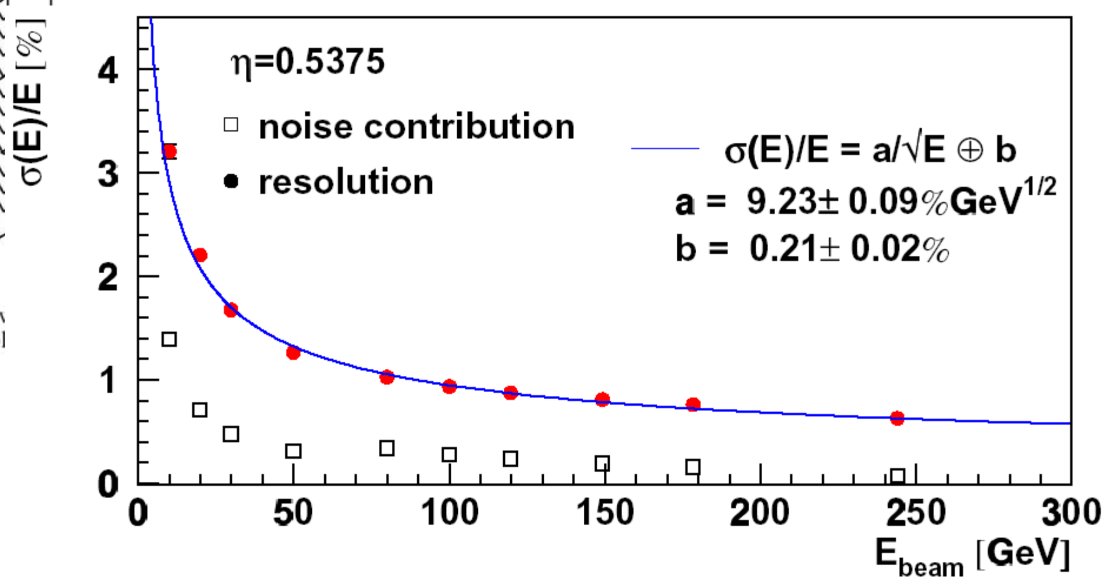
Sandwich of accordeon shaped lead absorber plates and electrodes, in liquid Argon (90°K)

(accordeon structure: no inter-module gaps)

Electrode readout allows high segmentation (transverse and longitudinal)

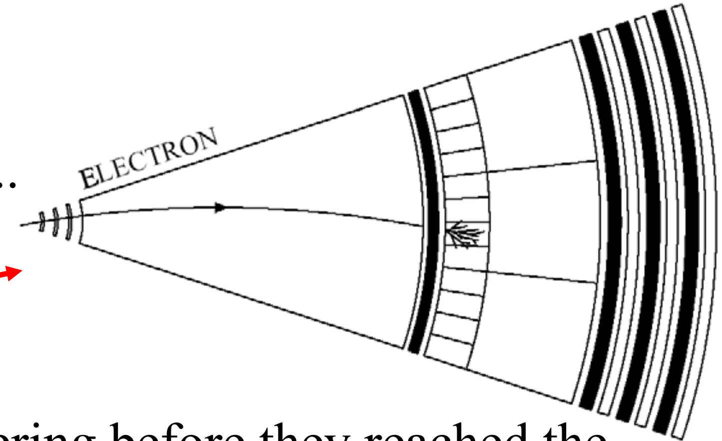






Preshower/presampler detectors

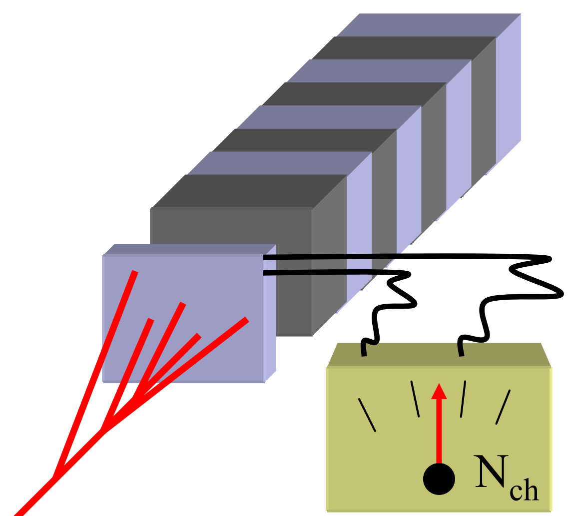
Particles pass a lot of matter before they reach the calorimeter: beam-pipe, tracking detectors, solenoid, .. (dead material)

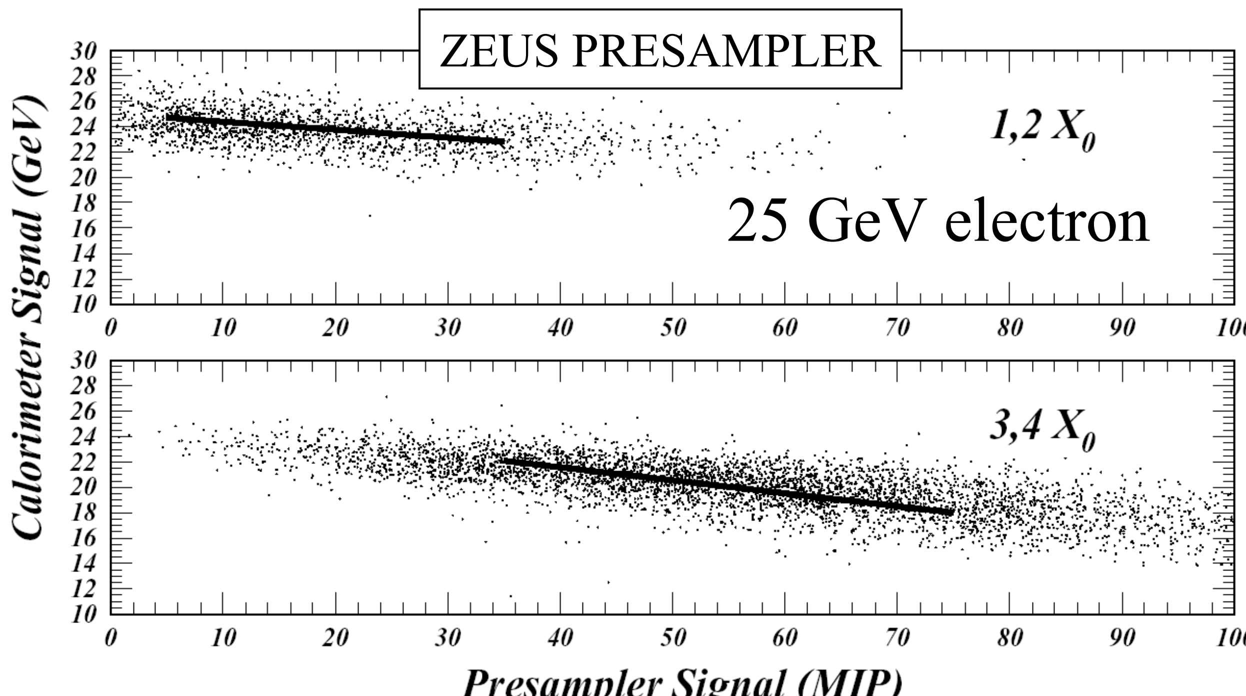


In particular electrons are likely to have started showering before they reached the calorimeter.

To estimate the lost energy one can measure the multiplicity when the shower enters the calorimeter.

<u>Pre-shower detector:</u>





The hadronic shower:

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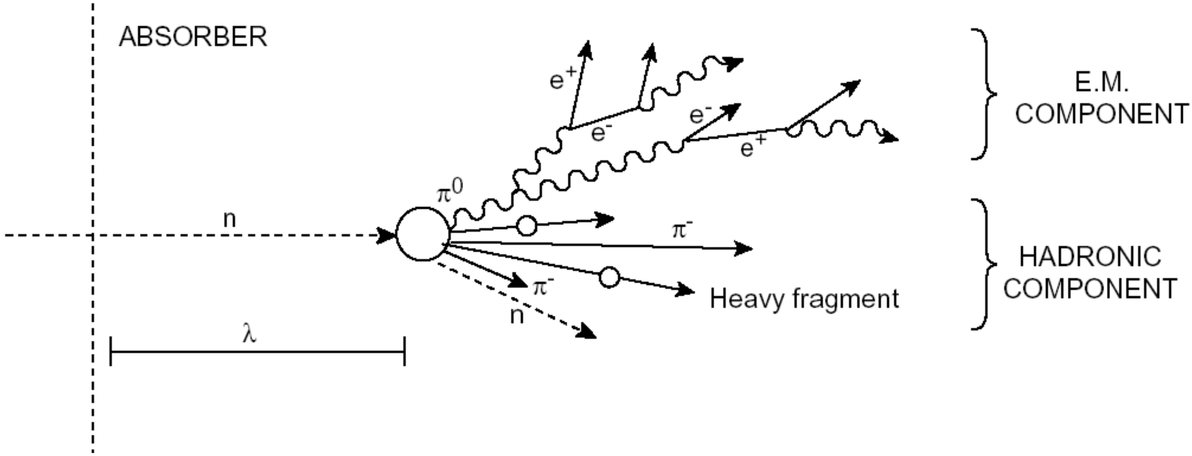
Dominated by inelastic nuclear interactions.

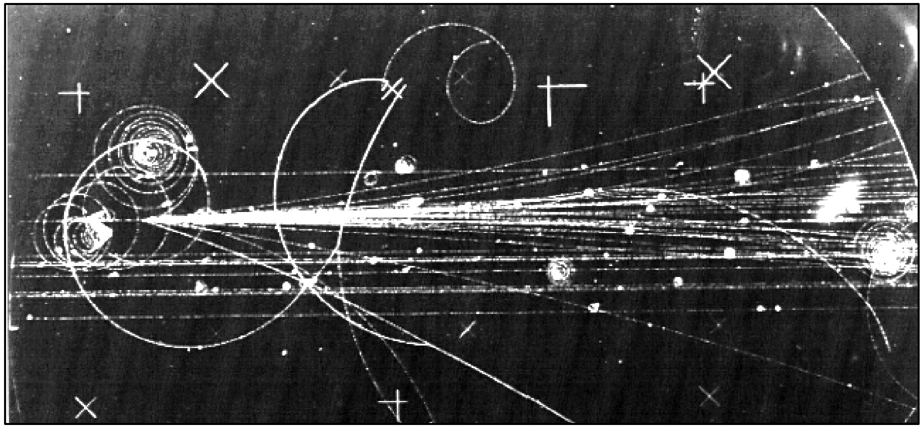
- pions
- low energy photons
- low energy neutrons
- Neutrinos
- Photons from π^0s



Cross section for inelastic nuclear interactions depends little on energy!

<ins>Interaction length</ins>: $\left(\lambda_I = 35\ \mathrm{g/cm^2}\ A^{1/3}\right)$

(mean-free-path for inelastic nuclear interaction, only depending on material!)



Calorimeter energy resolution for hadrons:

- E.M. and hadronic components vary strongly (event to event and with energy)
- Typically calorimeter response to hadronic part is lower, because some of the energy loss is unobserved (neutrinos, nuclear binding energy, ..)

Energy resolution for hadrons is much worse than for electrons/photons.

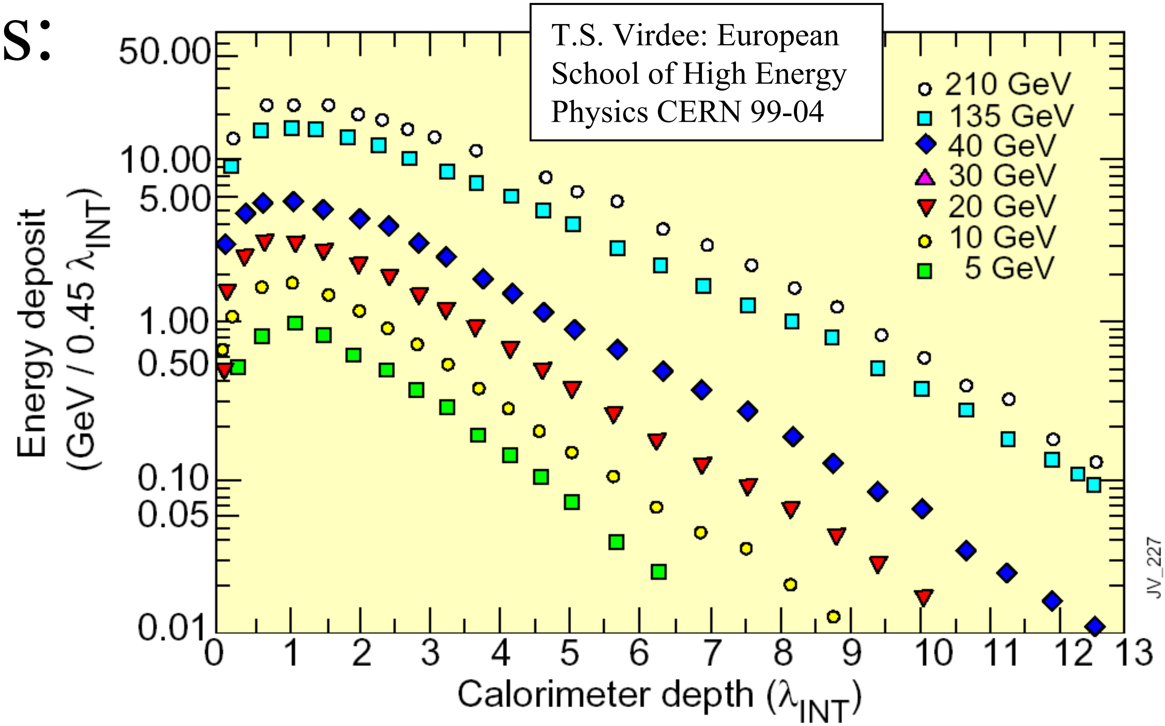
Shower depth hadrons:

For hadronic showers, interaction length is the relevant variable.

Hadronic showers are much deeper than e.m. showers!

$(\lambda_I >> X_0)$

Shower ends when remaining energy is too low to produce more pions.



Medium	Density ρ [g/cm^3]	Interaction length λ_{INT} [cm]
Copper (Cu)	**9.0**	**15.1**
Lead (Pb) (ATLAS)	**11.4**	**17.1**
Uranium (U) (ZEUS)	**19.0**	**10.5**
Iron (Fe)	**7.9**	**16.8**
Plastic scintillator	**~1.0**	**~80**
Concrete	**~2.5**	**~40**

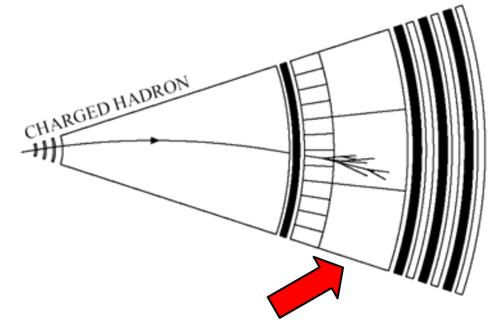
For "full" containment calorimeter thickness needed is about 9 λ_{INT}:

- **136 cm of copper**
- **154 cm of lead**
- **95 cm of uranium**
- **150 cm of iron**
- **~7 m of plastic-scintillator!!**
- **~3.6 cm of concrete**

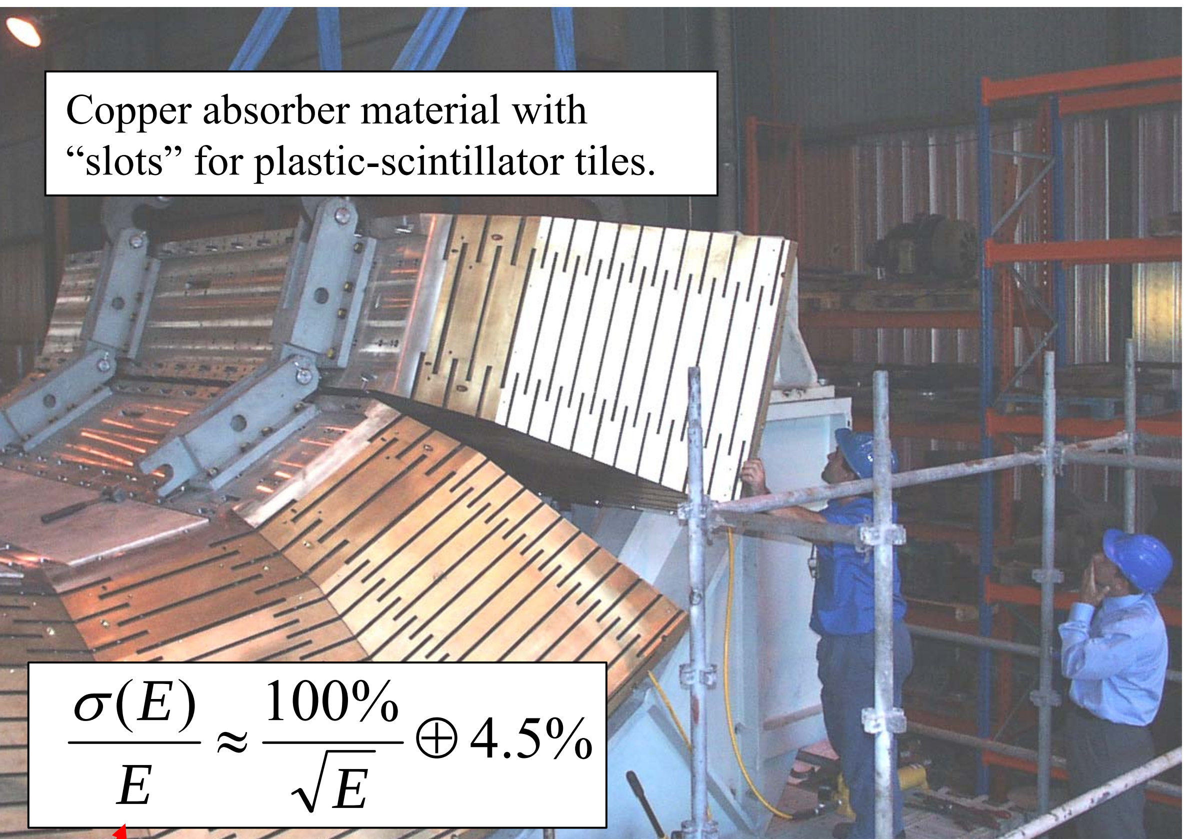
Hadron calorimeters need to be deep!

Hadron calorimeters:

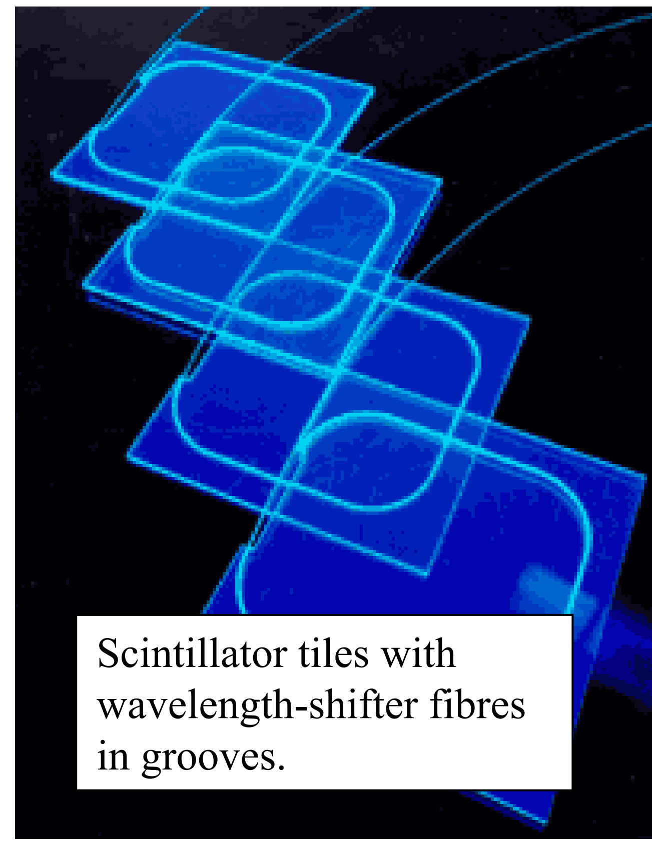
Typically: large mass of metal interspaced with some type of particle detection (scintillator tiles, gaseous particle detectors, ..)



Example: CMS hadron calorimeter



$$\frac{\sigma(E)}{E} \approx \frac{100\%}{\sqrt{E}} \oplus 4.5\%$$



(Refers to testbeam situation! In experiment ***E*** must be combined with ***E*** in e.m calorimeter.)

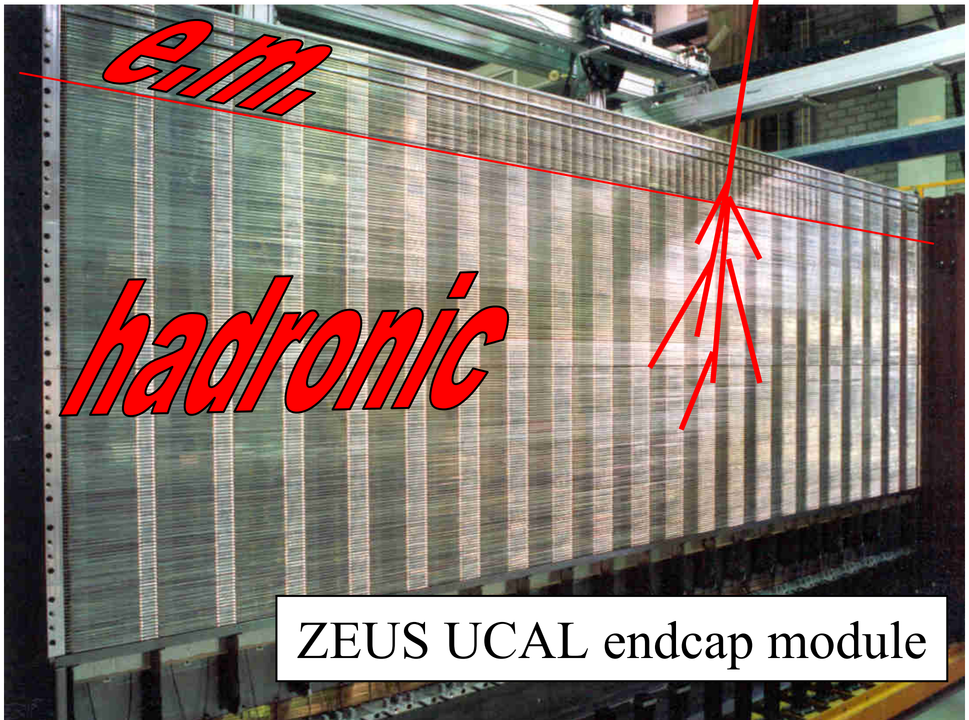
Compensating calorimeters (ZEUS/D0):

Typically in a calorimeter the response to the e.m. component ($\boldsymbol{E}_{\mathbf{em}}$) is greater than to the hadronic component ($\boldsymbol{E}_{\mathbf{had}}$). But we can manipulate this:

- increased relative thickness absorber suppresses $\boldsymbol{E}_{\mathbf{em}}$
- light nuclei in active material raise response to slow neutrons
- radioactive absorber material raises response to slow neutrons

If $\boldsymbol{E}_{\mathbf{em}}=\boldsymbol{E}_{\mathbf{had}}$ we have a <u>compensating</u> calorimeter.

Improved energy resolution for hadrons. (nice to have compensating e.m. part as well!)



ZEUS Calorimeter:

Combined e.m. & had. calorimeter!

Sandwich of depleted Uranium and plastic-scintillator tiles.

$$\frac{\sigma(E)_{\text{hadrons}}}{E} \approx \frac{35\%}{\sqrt{E}}$$

$$\frac{\sigma(E)_{\text{electrons}}}{E} \approx \frac{18\%}{\sqrt{E}} \text{ (rather poor!)}$$

Next Lecture

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II Gaseous tracking detectors

III Semi-conductor trackers

IV Calorimetry

V Particle identification