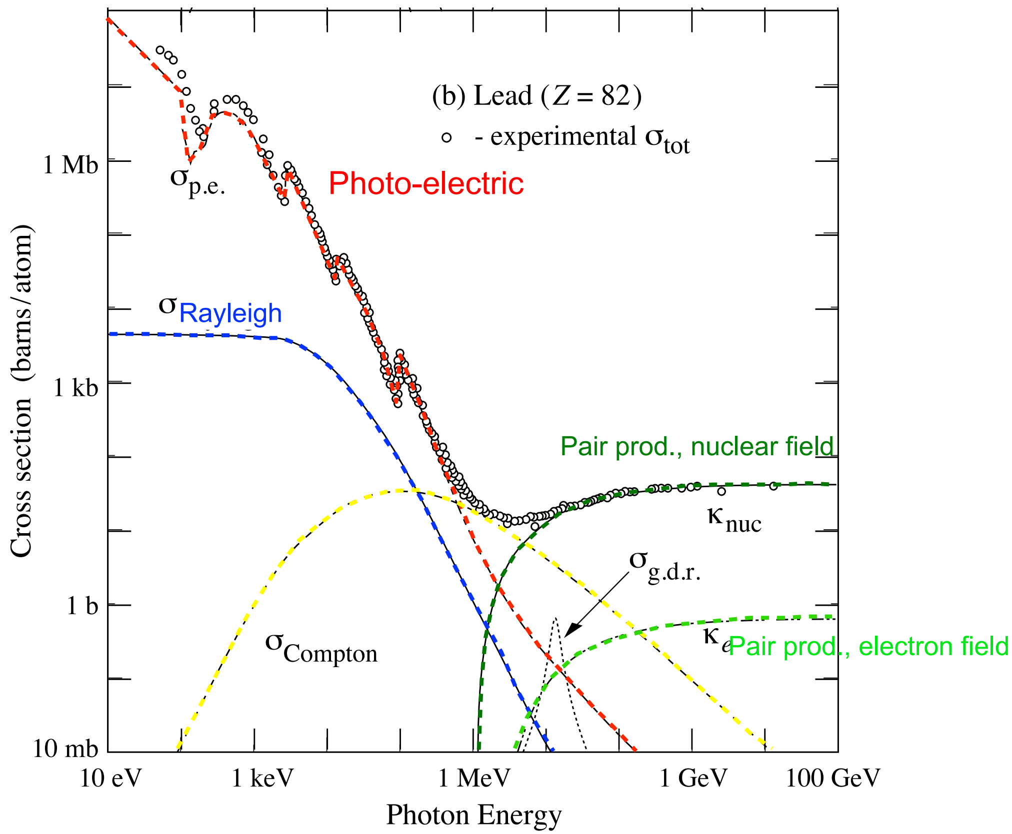
Photons: Interactions

- Photons appear in detector systems
  - as primary photons,
  - created in Bremsstrahlung and de-excitations
- Photons are also used for medical applications, both imaging and radiation treatment.

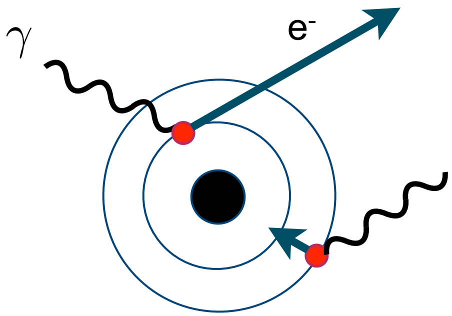
- Photons interact via 6 mechanisms depending on the photon energy:
  - < few eV: molecular interactions
  - < 1 MeV: photoelectric effect
  - < 1 MeV: Rayleigh scattering
  - ~ 1 MeV: Compton scattering
  - > 1 MeV: pair production
  - > 1 MeV: nuclear interactions



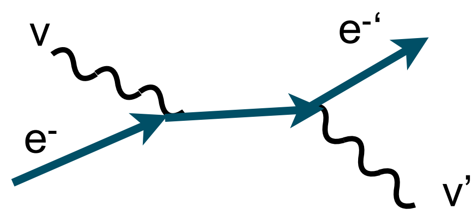
Photons: Interactions

- Most dominating effects:

Photo-Effect

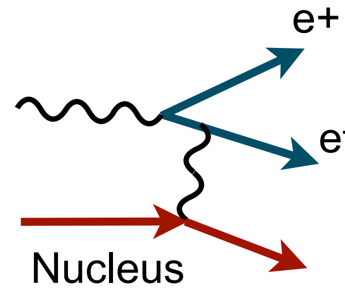


Compton-Scattering



$$\gamma + e \rightarrow \gamma' + e'$$

Pair creation



A γ is absorbed and photo-electron is ejected.

- the γ disappears,
- the photo-electron gets an energy

$$E_{\mathrm{p.e}} = E_\gamma - E_{\mathrm{binding}}$$

Elastic scattering of a photon with a free electron

$$E'_\gamma = \frac{1}{1+\epsilon(1-\cos\theta_\gamma)}$$

Only possible in the Coulomb field of a nucleus (or an electron) if

$$E_\gamma \geq 2m_e c^2$$

~1.022 MeV

⇨ Reduction of photon intensity with passage through matter:

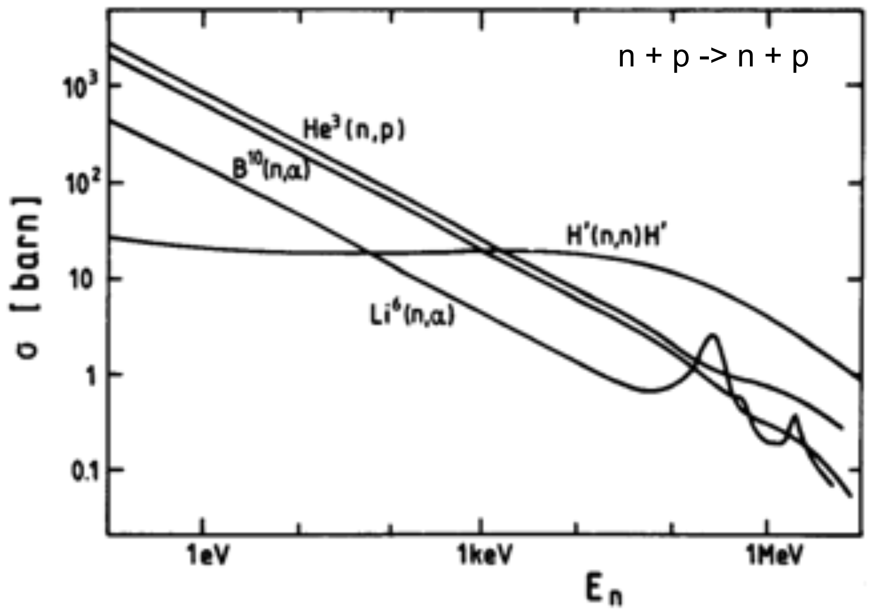
$$I(x) = I_0 e^{-\mu x}$$

Interactions of Neutrons

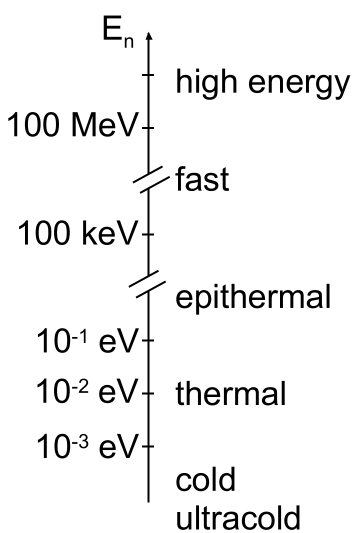
- Neutron interaction is based only on strong (and weak) nuclear force.
- To detect neutrons, one has to create charged particles.
- Possible neutron conversion and elastic reactions …

$$\left.\begin{array}{r} n + {}^{6}\mathrm{Li} \rightarrow \alpha + {}^{3}\mathrm{H} \\ n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} \\ n + {}^{3}\mathrm{He} \rightarrow p + {}^{3}\mathrm{H} \end{array}\right\} \quad E_n < 20\mathrm{MeV}$$

$$n + p \rightarrow n + p \qquad E_n < 1\mathrm{GeV}$$



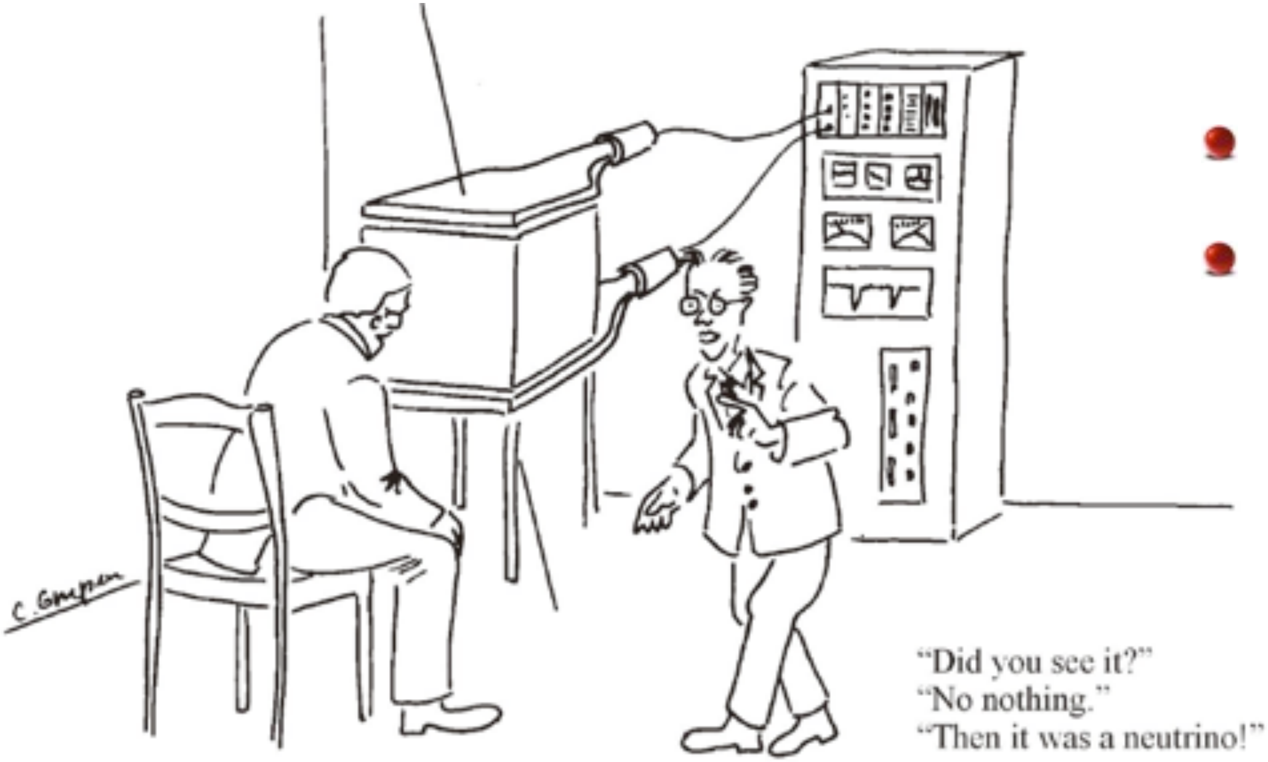
Plot: H. Neuert, Kernphysikalische Messverfahren, 1966



In addition there are…

- inelastic reactions → hadronic cascades E_n > 1 GeV
- same detection principals as for other hadrons (calorimeter)

A Short Word on Neutrinos…



Claus Grupen, Particle Detectors, Cambridge Uni. Press 1996

- Neutrons react very weakly with matter
- Cross section for $\nu_e + n \to e^- + p$ is around 10^{-43} cm^{-2}.
  - 1m Iron: probability 10^{-17}

- In collider experiments fully hermetic detectors allow indirect detection
  - Sum up all visible energy and momentum in detector
  - Missing energy and momentum belong to neutrino(s)

Summary Part 1

Ionisation and Excitation:

- Charged particles traversing material are **exciting and ionising** the atoms.
- Average energy loss of the incoming charged particle: good approximation described by the **Bethe Bloch** formula.
- The energy loss fluctuation is well approximated by the Landau distribution.

Multiple Scattering and Bremsstrahlung:

- Incoming particles are **scattering off** the atomic nuclei which are partially shielded by the atomic electrons.
- Measuring the particle momentum by deflection of the particle trajectory in the magnetic field, this scattering imposes a lower limit on the momentum resolution of the spectrometer.
- The deflection of the particle on the nucleus results in an acceleration that causes emission of Bremsstrahlungs-Photons. These photons in turn produced e+e- pairs in the vicinity of the nucleus….

A short summary

$\pi^- + p$

16 GeV

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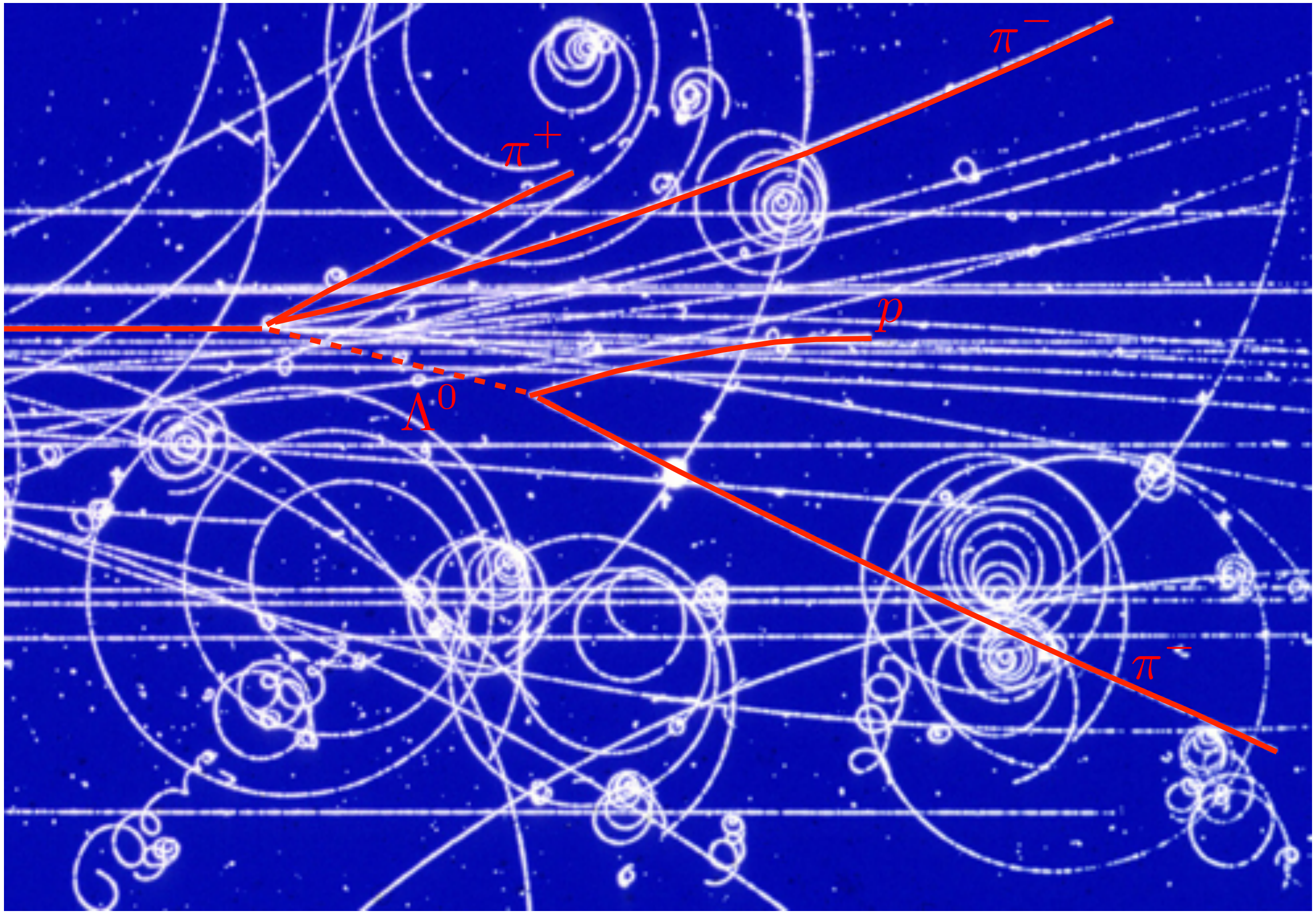


Lifetime of lambda:
2.6 10^{-10} sec
-> a few cm

$$\pi^- + p \rightarrow K_s^0 + \Lambda$$

?

The decay of a lambda particle in the 32 cm hydrogen bubble chamber

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

IV. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers

V. **Examples from the real life**

Wednesday

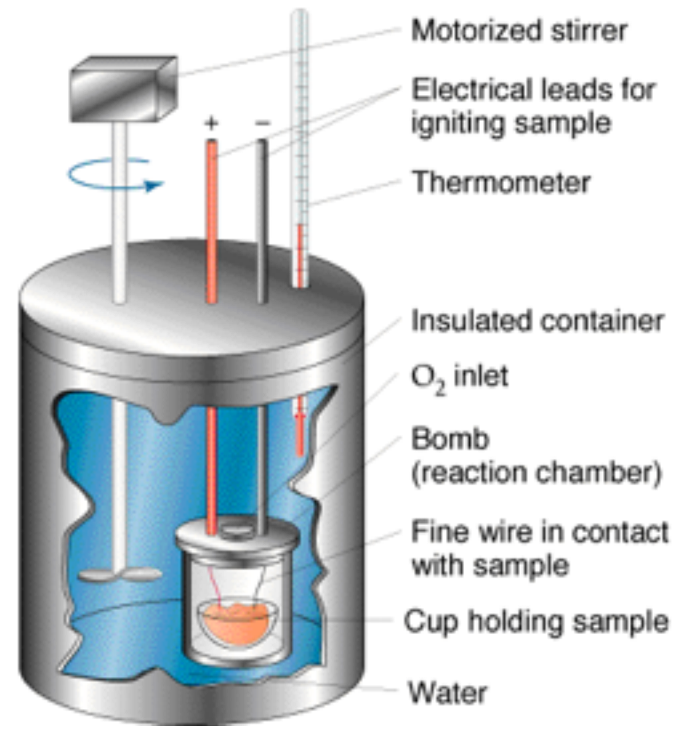
Thursday

III. Calorimeters

Calorimetry: The Idea behind it ....

- Calorimetry originated in thermo-dynamics
  - The total energy released within a chemical reaction can be measured by measuring the temperature difference
- In particle physics:
  - Measurement of the energy of a particle by measuring the total absorption

Ice-calorimeter from Antoine Lavoisier's 1789 *Elements of Chemistry*.



Picture: Francois G. Amar

- What is the effect of a 1 GeV particle in 1 litre water (at 20°C)?

$$\Delta T = E / (c \cdot M_{water}) = 3.8\cdot 10^{-14}\,\mathrm{K}\ !$$

Calorimetry: Overview

- Basic mechanism for calorimetry in particle physics:
  - formation of electromagnetic
  - or hadronic showers.
- The energy is converted into ionisation or excitation of the matter.

Charge

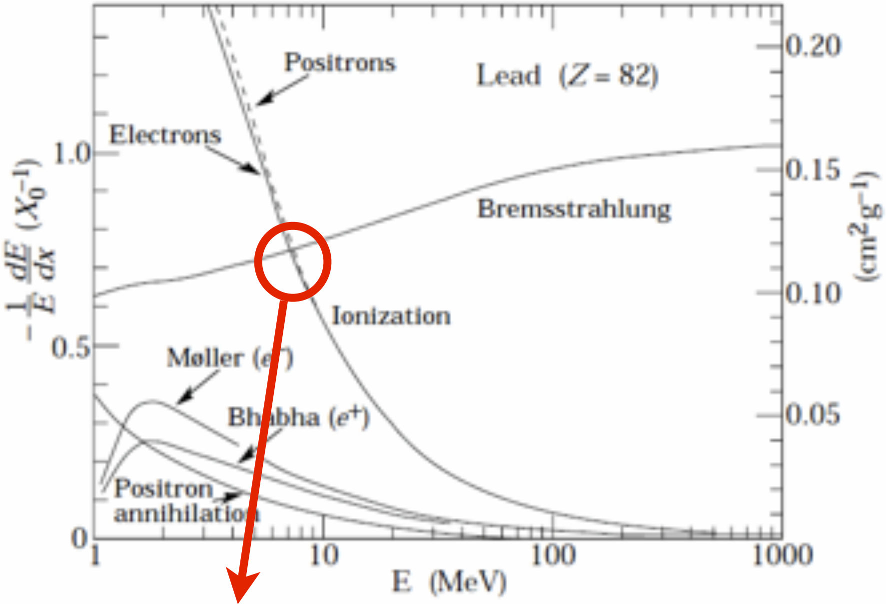
Scintillation light

Cerenkov light

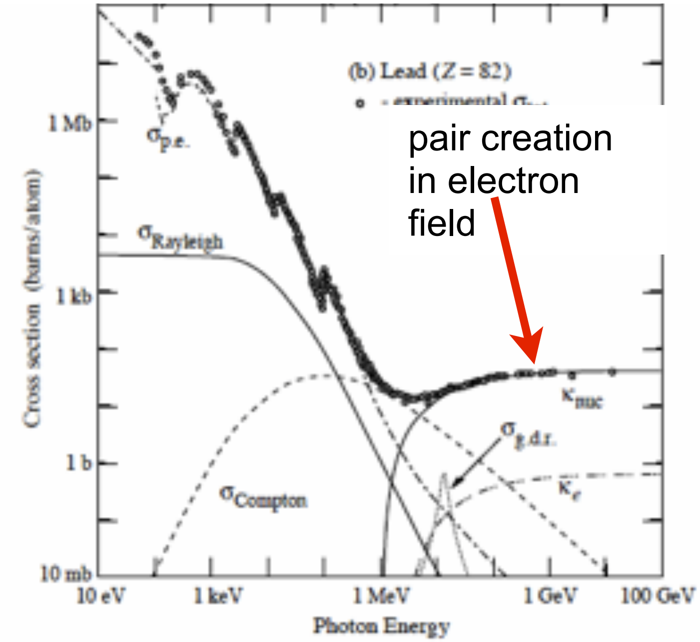
- Calorimetry is a "destructive" method. The energy and the particle get absorbed!
- Detector response $\propto E$
- Calorimetry works both for charged ($e^{\pm}$ and hadrons) and neutral particles (n,γ) !

Reminder

Electrons



Photons



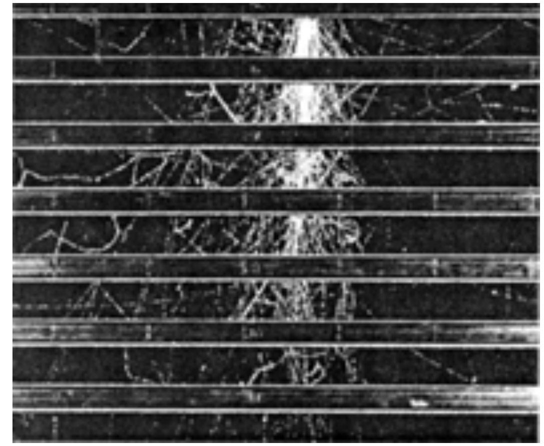
- **Critical energy:** the energy at which the losses due to ionisation and Bremsstrahlung are equal
- **Radiation length** defines the amount of material a particle has to travel through until the energy of an electron is reduced by Bremsstrahlung to 1/e of its original energy $\langle E_e(x)\rangle \propto e^{\frac{x}{X_0}}$

empirical: $X_0 = \frac{716.4\,A}{Z(1+Z)\,ln(287/\sqrt{Z})}\,\frac{g}{cm^2} \propto \frac{A}{Z^2}$

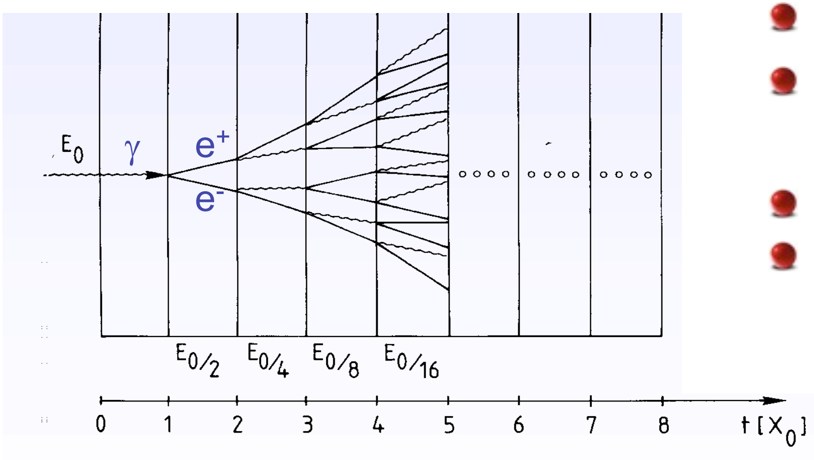
Electromagnetic Showers

- High energetic particles: forming a shower if passing through (enough) matter.
- An alternating sequence of interactions leads to a cascade:
  - Primary γ with E_0 energy produces e+e- pair with 54% probability in layer X_0 thick
  - On average, each has $E_0/2$ energy
  - If $E_0/2 > E_c$, they lose energy by Bremsstrahlung

Cloud chamber photo of electromagnetic cascade between spaced lead plates.



Pic: MIT cosmic ray group



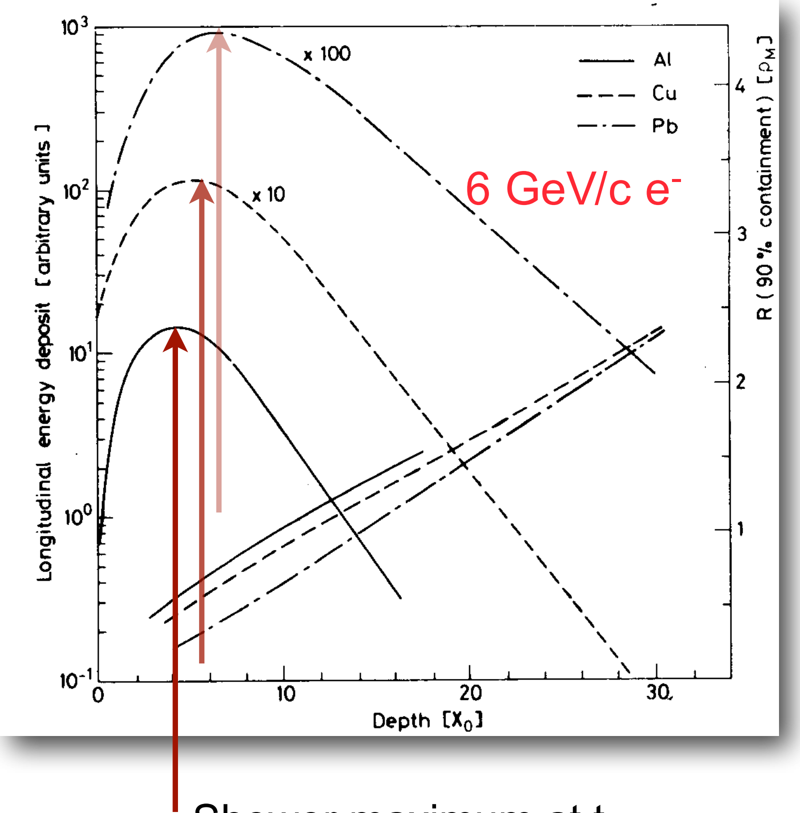
- Next layer X_0, charged particle energy decreases to $E_0/(2e)$
- Bremsstrahlung with an average energy between $E_0/(2e)$ and $E_0/2$ is radiated
- Radiated γs produce again pairs
- After t radiation lengths
  - number of particles $N \simeq 2^t$
  - each with average energy $E_N \simeq \frac{E_0}{2^t}$

EM Shower Properties

- Shower continues until energy of particles below critical energy.

$$E(t_{max}) = \frac{E_0}{2^{t_{max}}} = E_c$$

$$t_{max} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \qquad N_{max} \simeq \frac{E_0}{E_c}$$

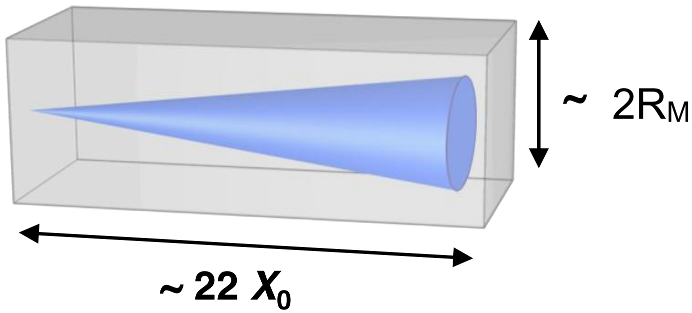


Shower maximum at t_{max}

- Simple model only, for more details MC simulation required.
- Shower curve should rise rapidly to a peak value and then fall to zero.
- The broad peak of the experimental curve can be interpreted in terms of a **energy spread** of the incoming particles.
- Long tail due to **muon interactions** producing knock-on electrons capable of making a contribution to the cascade process.

EM Shower Properties

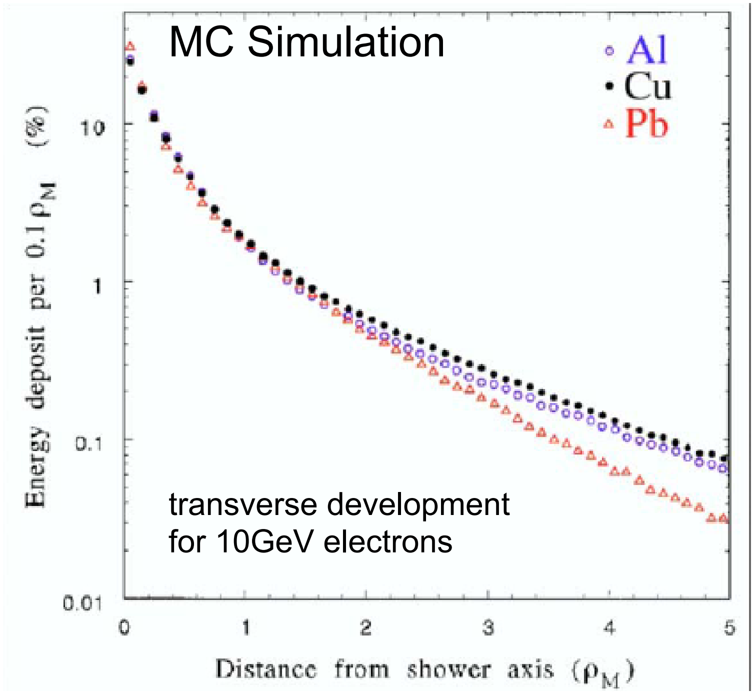
- Longitudinal development governed by the radiation length X_0.
- Lateral spread due to electron undergoing multiple Coulomb scattering:
  - 95% of the shower cone is located in a cylinder with radius 2 RM
  - Beyond this point, electrons are increasingly affected by multiple scattering



- Lateral width scales with the **Molière radius *R_M***
  - Important parameter for shower separation

$$R_M = X_0 \frac{E_s}{E_c} = 21.2MeV * \frac{X_0}{E_c}$$

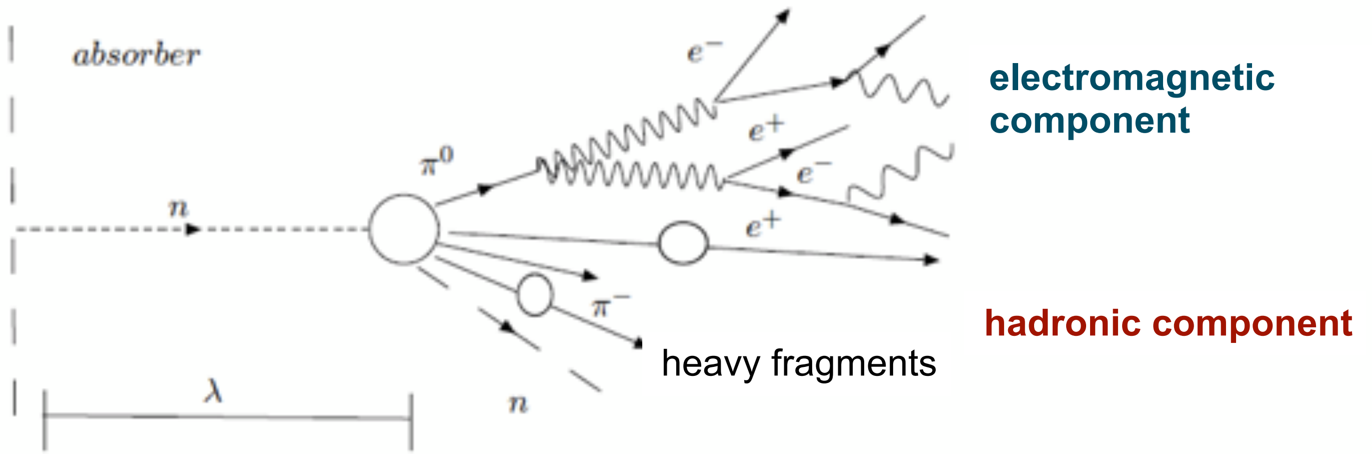
$$E_S = m_e c^2 \sqrt{4\pi/\alpha} = 21.2MeV$$



Example:
E_0= 100 GeV
in lead glass E_c=11.8 MeV
$\rightarrow N_c \approx 13$, $t_{95\%} \approx 23$
$X_0 \approx 2$ cm, RM= 1.8·$X_0 \approx 3.6$ cm

Hadronic Cascade

- Within the calorimeter material a hadronic cascade is build up: in inelastic nuclear processes more hadrons are created



The length scale of the shower is given in means of the nuclear reaction length λ_I

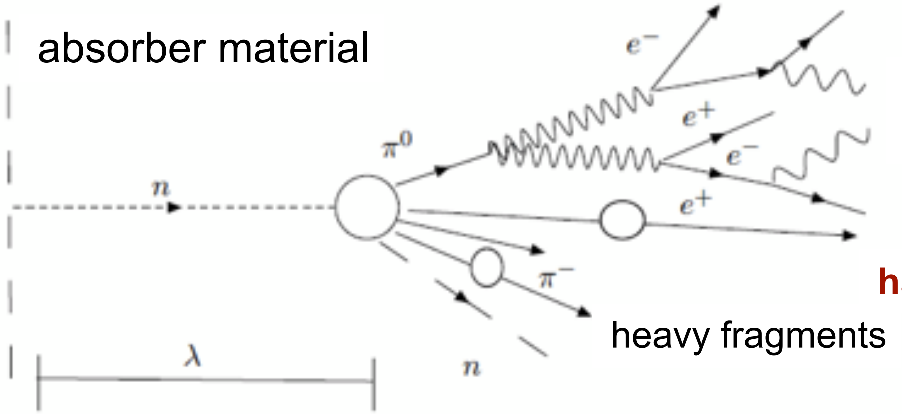
$$\lambda_I = \frac{A}{N_A \sigma_{total}}$$

total cross section for nuclear processes

	λ_I	X_0
Polystyren	81.7 cm	43.8 cm
PbWO	20.2 cm	0.9 cm
Fe	16.7 cm	1.8 cm
W	9.9 cm	0.35 cm

Compare X_0 for high-Z materials, we see that the size needed for hadron calorimeters is large compared to EM calorimeters.

Hadronic Cascade: The Details



Hadronic showers are way more complicated than em showers.

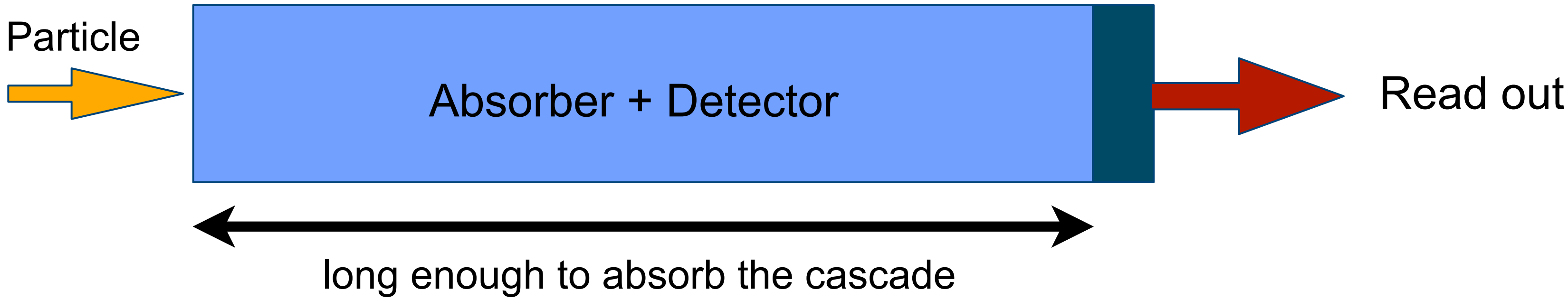
Pic: T. Ferbel. Experimental Techniques in High Energy Physics.

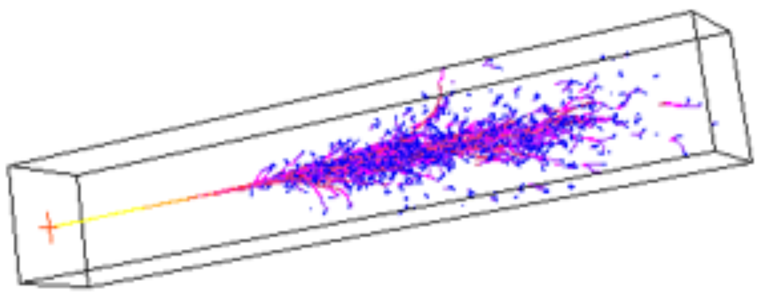
- Different processes are created by the impinging hadron:
  - high energetic secondary hadrons taking a significant part of the momentum of the primary particle [e.g. O(GeV)]
  - a significant part of the total energy is transfered into nuclear processes: nuclear excitation, spallation, ... ➠ Particles in the MeV range
  - neutral pions (1/3 of all pions), decay instantaneously into two photons ➠ start of em showers
  - Breaking up of nuclei (binding energy) neutrons, neutrinos, soft γ's, muons

invisible energy
-> large energy fluctuations
-> limited energy resolution

Calorimeter Types

- Two different types of calorimeters are commonly used: Homogeneous and Sampling Calorimeter
- **Homogeneous Calorimeter**
  - The absorber material is active; the overall deposited energy is converted into a detector signal
  - Pro: very good energy resolution
  - Contra: segmentation difficult, selection of material is limited, difficult to built compact calorimeters





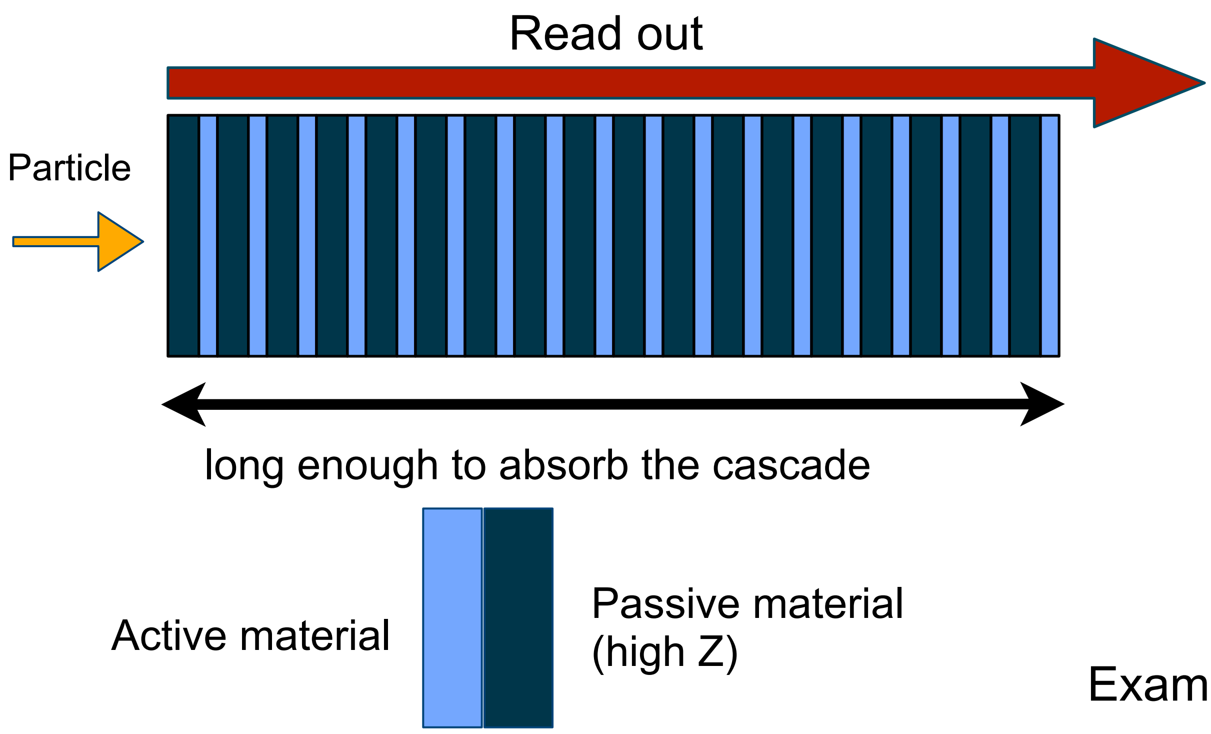
Pic: Cornell

Example: Crystal calorimeter

Sampling Calorimeter

Sampling Calorimeter

- A layer structure of passive material and an active detector material; only a fraction of the deposited energy is "registered"
- Pro: Segmentation (transversal and lateral), compact detectors by the usage of dense materials (tungsten, uranium,…)
- Contra: Energy resolution is limited by fluctuations



Important parameter:
Sampling Fraction

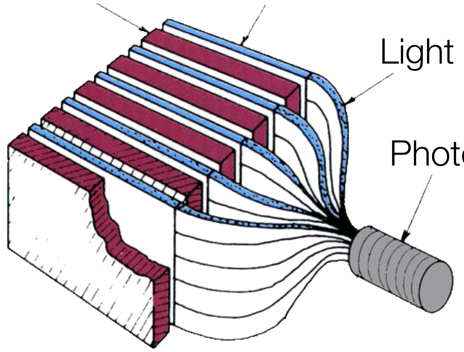
The fraction of the energy of a passing particle seen by the active material.

Typically in the percent range

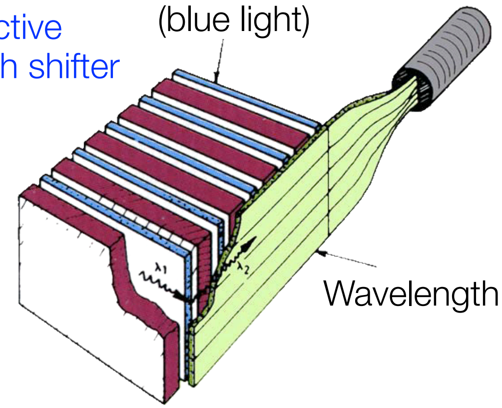
Example: ZEUS Uranium Calorimeter

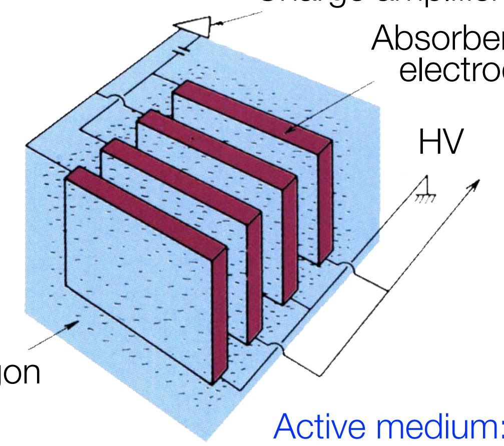
Sampling Calos: Possible Setups

Scintillators as active layer;
signal readout via photo multipliers



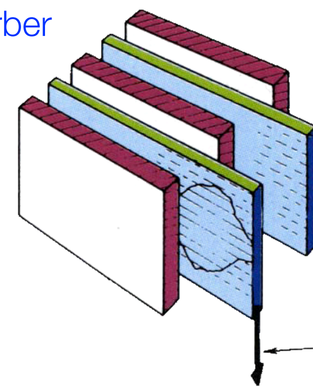
Scintillators as active layer; wave length shifter to convert light





Active medium: LAr; absorber embedded in liquid serve as electrods

Ionization chambers between absorber plates



Calorimeter: Important Parameter (1)

- The relative **energy resolution** of a calorimeter is parametrised:

$$(\frac{\Delta E}{E})^2 = (\frac{c_s}{\sqrt{E}})^2 + (\frac{c_n}{E})^2 + (c_c)^2$$

- **Stochastic** term c_s
  - the resolution depends on intrinsic shower fluctuations, photoelectron statistics, dead material in front of calo, and sampling fluctuations
- **Noise** term c_n
  - Electronic noise, radioactivity, i.e. dependent of the energy
- **Constant** term c_c
  - Energy independent term contributing to the resolution: due to inhomogenities with in the detector sensitivity, calibration uncertainties and radiation damage

Losses of Resolution:

- **Shower not contained** in detector → fluctuation of leakage energy; longitudinal losses are worse than transverse leakage.
- **Statistical fluctuations** in number of photoelectrons observed in detector.
- **Sampling fluctuations** if the counter is layered with inactive absorber.
- ….

10 minutes coffee break !