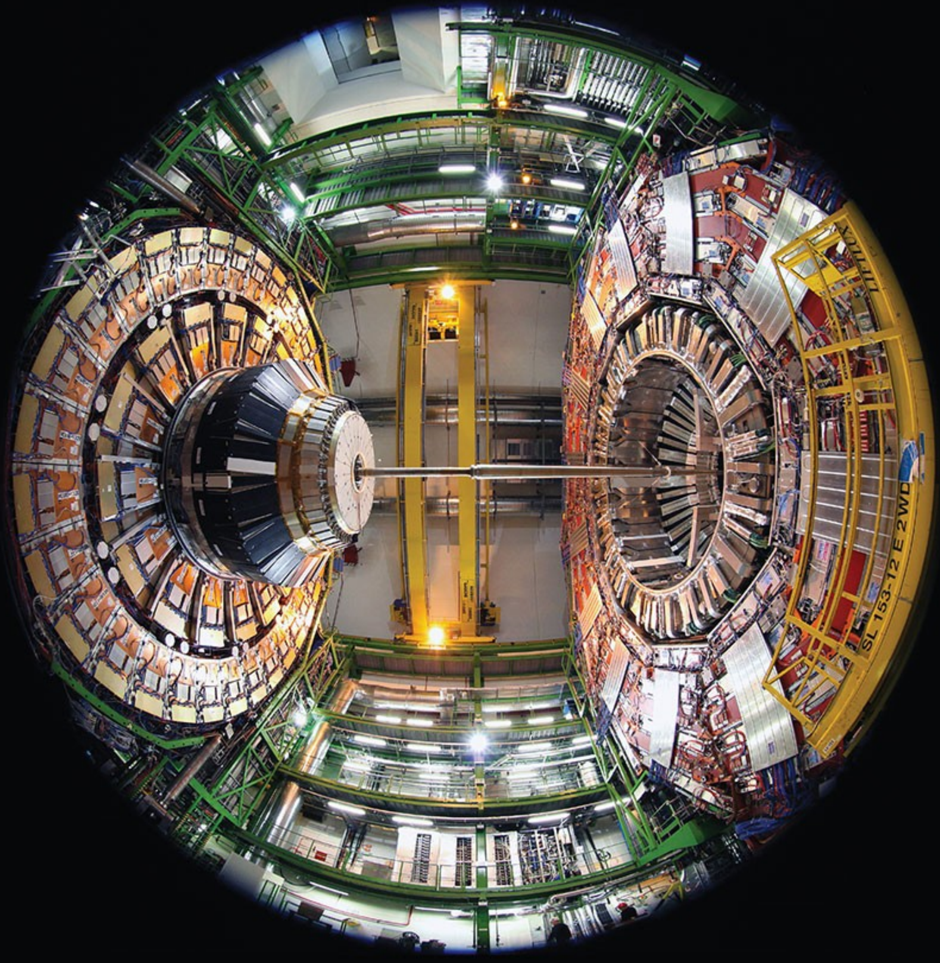
Calorimetry in high energy physics

Part 1



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Lecture plan

What is calorimeter in HEP?

Electromagnetic and hadronic showers

Detection techniques

Calorimeter response & resolution

Closing remarks

These slides are available on the Indico page of ESIPAP
There is also an extended version containing additional topics, for your curiosity

Reference

- The following lecture was built upon several lectures and books
- Lectures
  - C. Ochando, *Lectures on Calorimetry*, ESIPAP 2019
  - I. Wingerter-Seez, *Calorimetry: Concepts and Examples*, ESIPAP 2016
  - E. Garutti, *The art of calorimetry* (link)
  - R. Wigmans, *Calorimetry*, EDIT 2011
  - V. Boudry, *La Calorimetrie*, Ecole du detecteur a la mesure 2013
  - D. Cockerill, *Introduction to Calorimeters*, Southampton Lecture 2016
  - A. Zabi, *Instrumentation for High Energy Physics*, TES-HEP 2016
  - P. Janot, *Particle-Flow event reconstruction from LEP to LHC*, EDIT 2011
- Books
  - R. Wigmans, *Calorimetry, Energy measurement in Particle Physics*, Oxford science publication
  - C. Gruppen & B. Shwartz, *Particle detectors*, Cambridge monographs on particle physics, nuclear physics and cosmology

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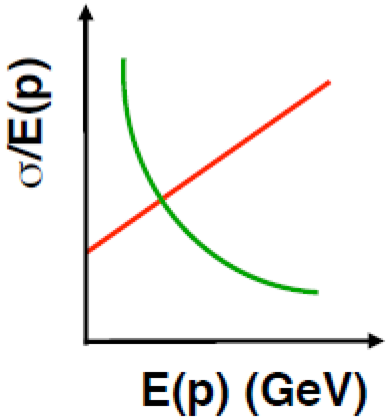
Closing remarks

What is a calorimeter (in HEP)?

- Originally a "calorimeter" is an instrument measuring heat ("calor" in latin) produced by some reactions (chemical or physical)
  - In HEP it is quite different
- Detection of particles through **total absorption** in a block of matter
- Complementary to tracking detectors
  - Trackers measures charged particle bending
  - Calorimeters **measure absorbed energy**

Resolution



Tracking

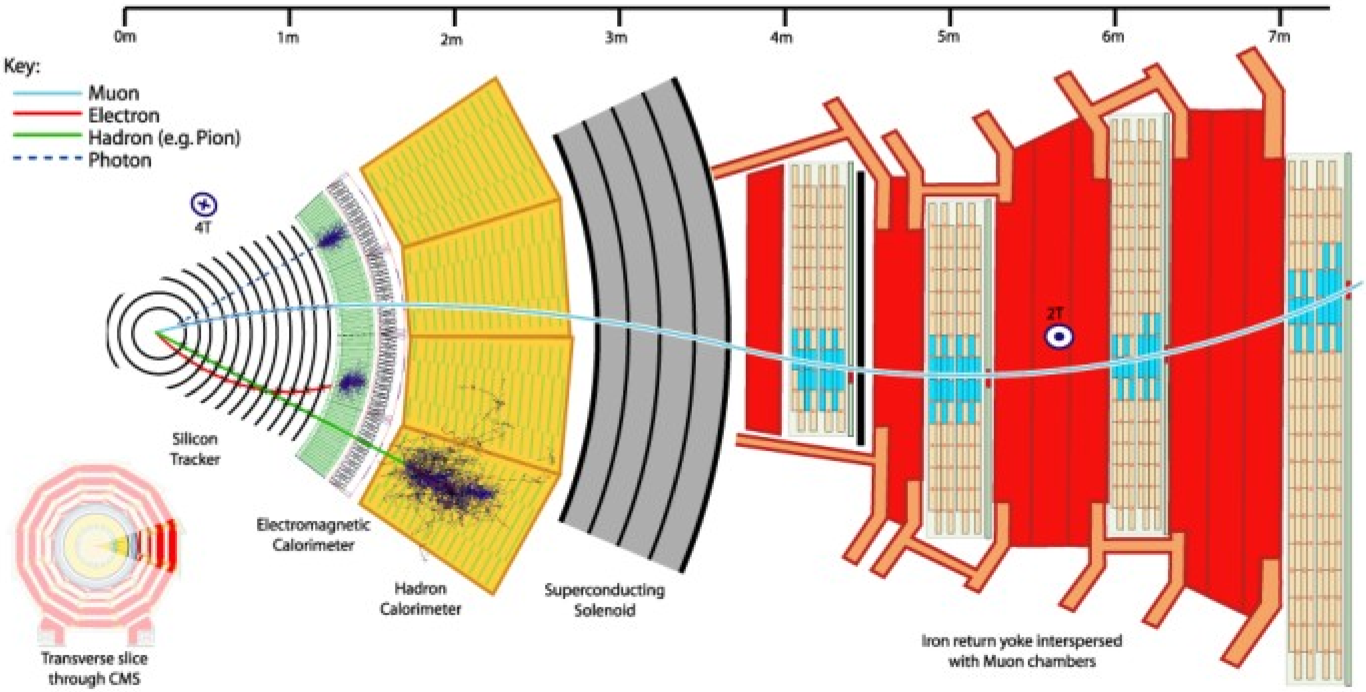
$$\frac{\sigma(p)}{p} = ap \oplus b$$

Calorimetry

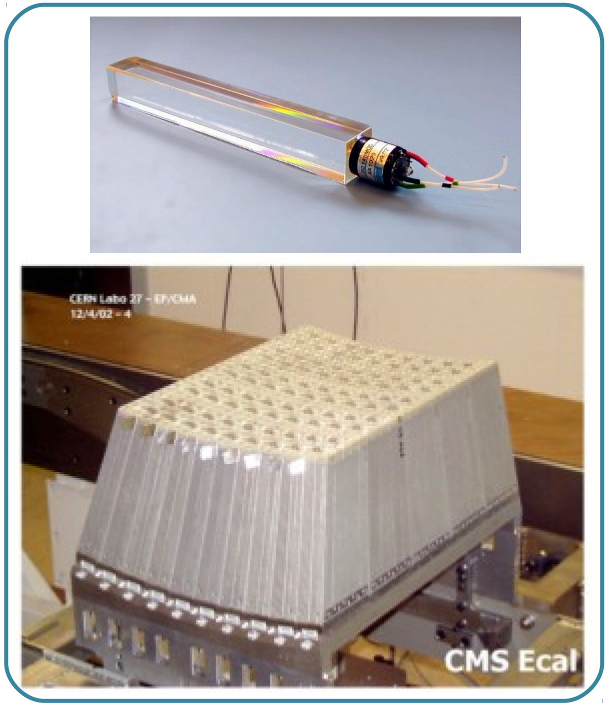
$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

- Calorimeters can **measure both charged and neutrals**

Example 1: CMS ECAL



CMS ECAL crystal and module



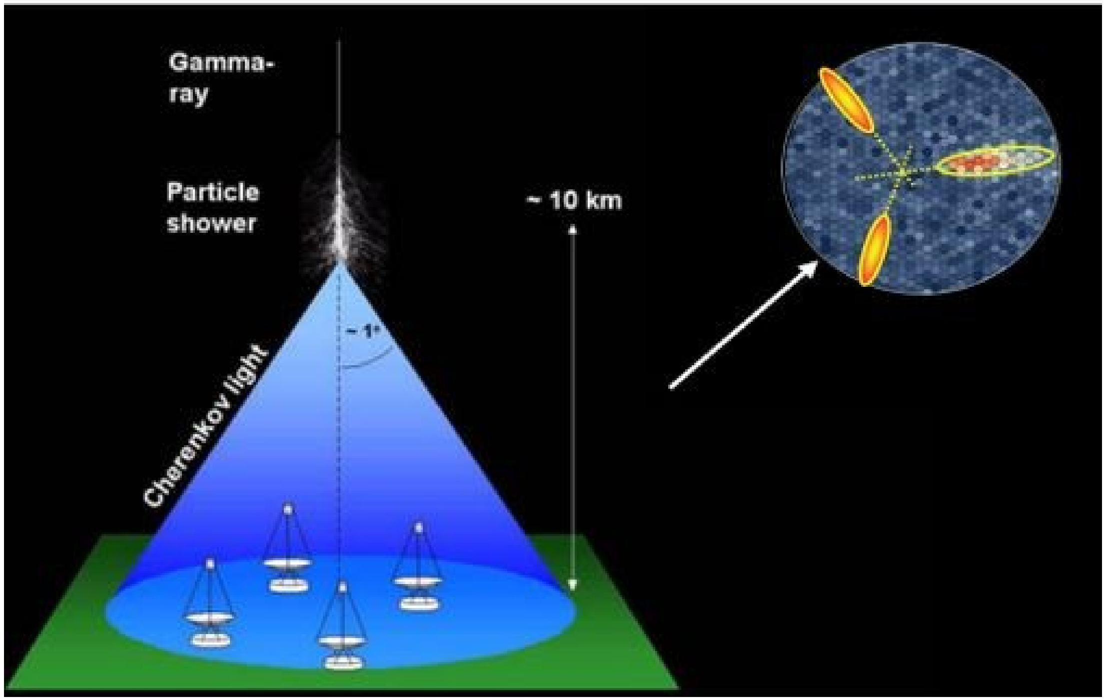
- CMS: typical **onion-like** detector **structure**
  - Tracking + magnet (curvature of charged particles)
  - EM and hadronic calorimeters
- CMS ECAL
  - **Scintillating crystals** + **photodiodes**

Example 2: HESS

The 5 HESS telescopes

- Explore cosmic gamma rays
  - Interaction with the **atmosphere**
  - Emission of **Cerenkov light**
- Telescopes record this Cerenkov light on the ground

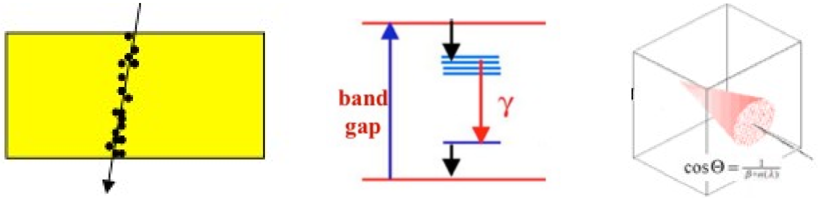
Detection principles



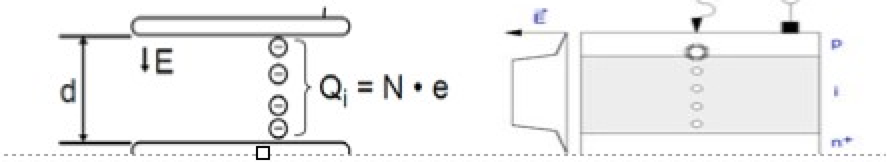
Calorimeter: principles

Particles interact with matter
The material depends on the particle

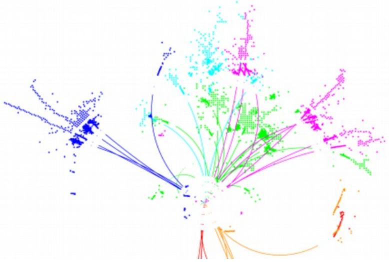
Energy lost transferred to detectable signal
Light, electric signal, etc.



Signal collected and acquired
With electronics



Calibration and reconstruction
Infer initial particle energy, position and type



Everything together
Build an experimental setup
Many constraints to be satisfied

Lecture plan

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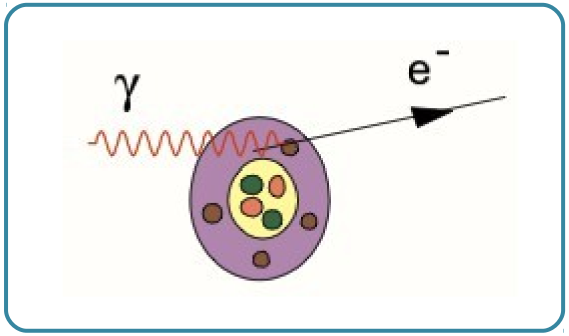
Electromagnetic interactions with matter

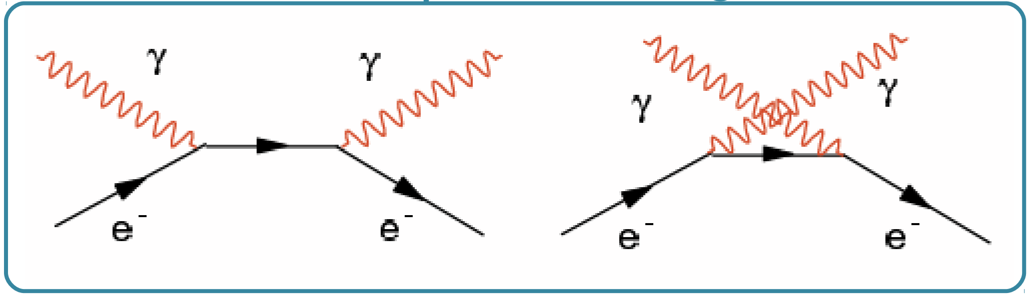
Photons | **Electrons**

Low energy

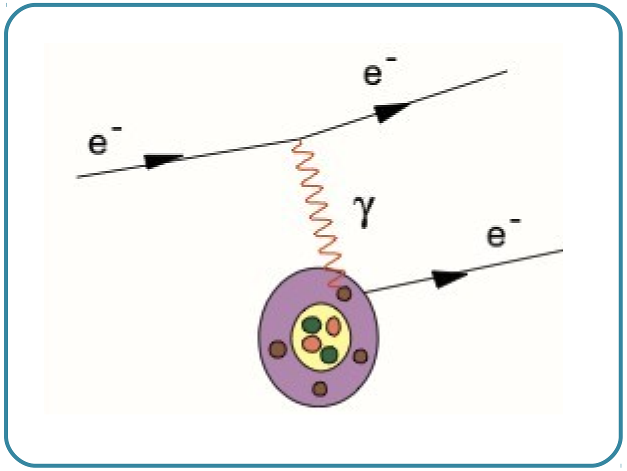
Photoelectric effect



Compton scattering

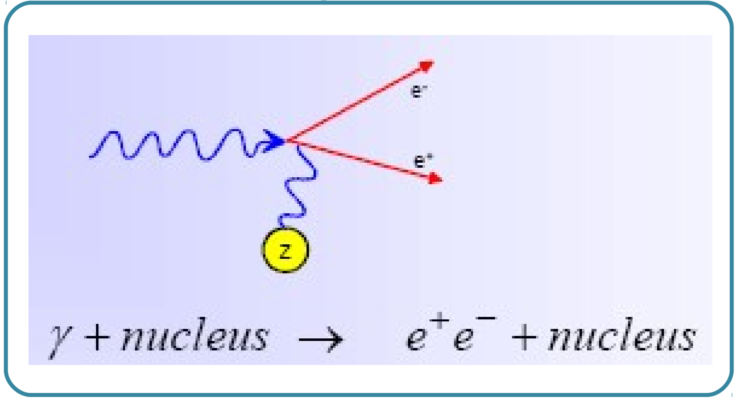


Ionisation



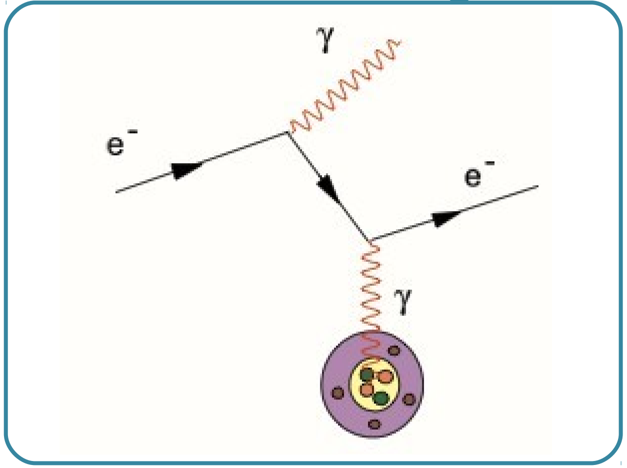
High energy

Pair production



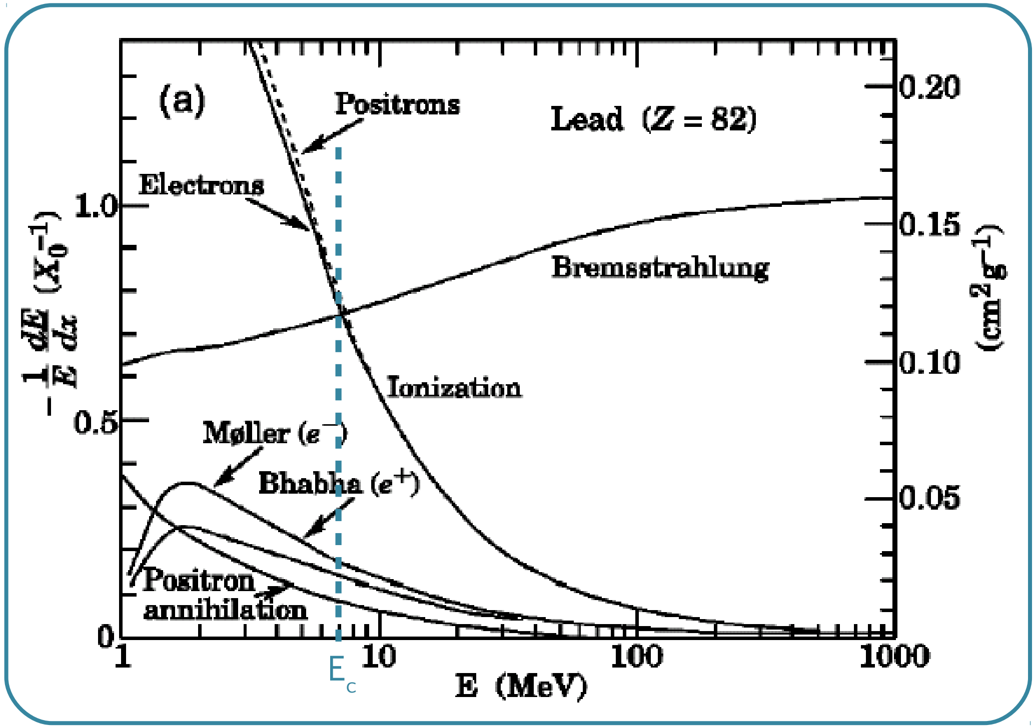
$$\gamma + nucleus \rightarrow e^{+}e^{-} + nucleus$$

Bremsstrahlung

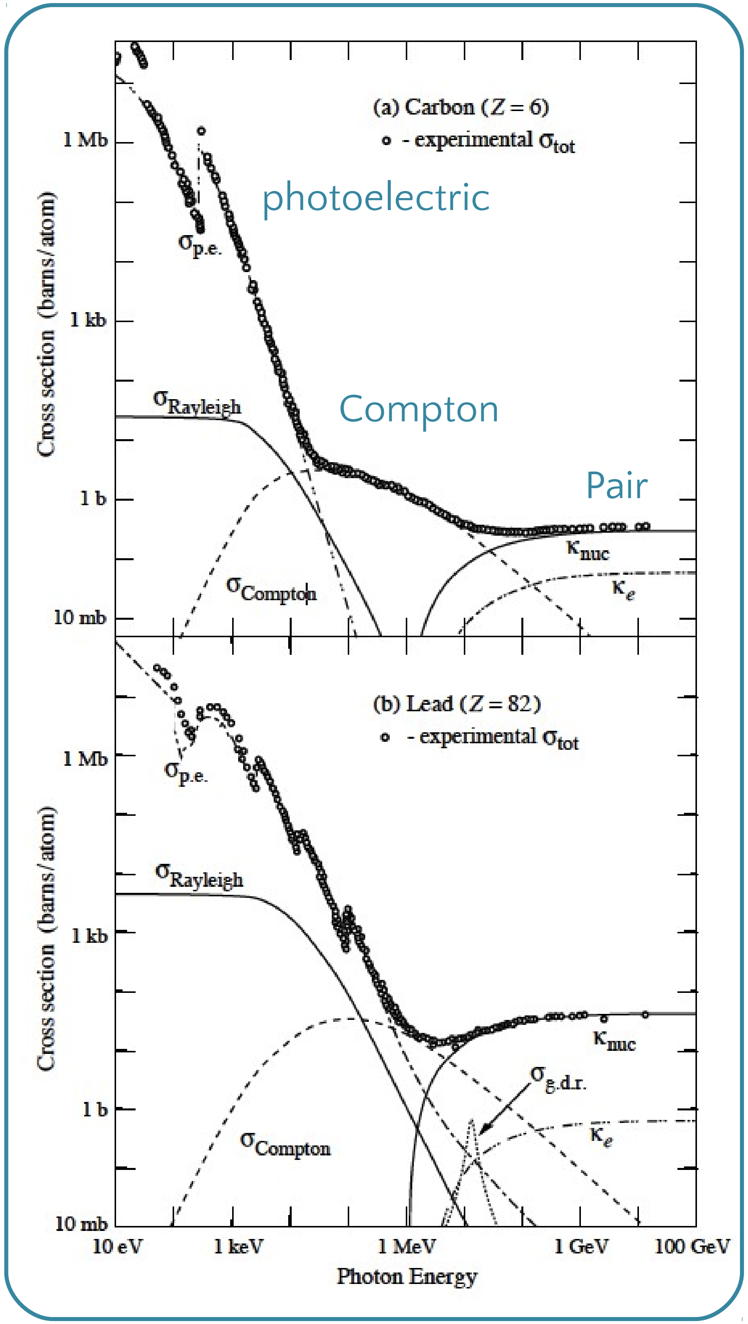


Dominant processes

Electrons



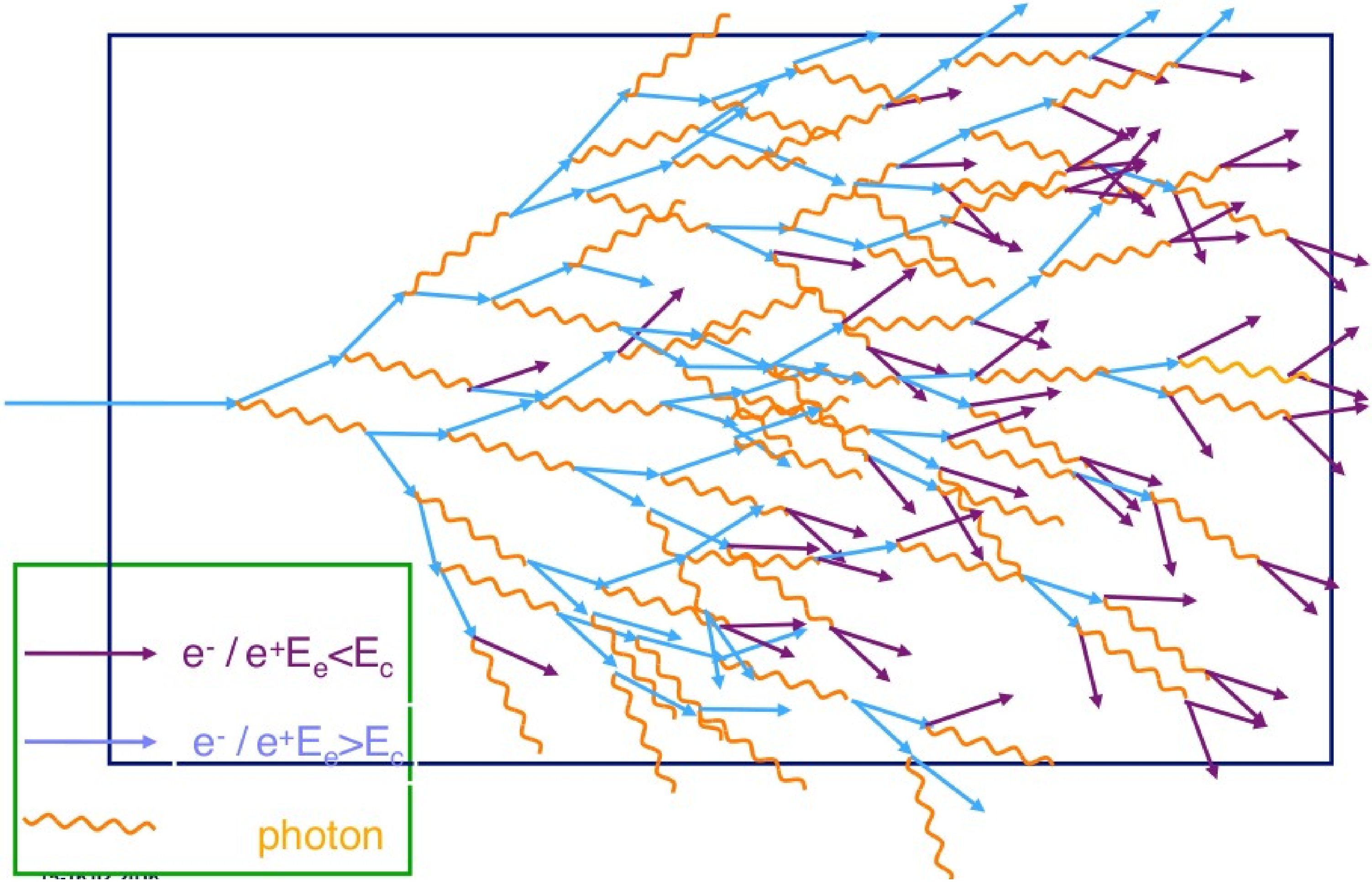
Photons



- High energy electrons: **Bremsstrahlung**
- High energy photons: **Pair creation**
- Below critical energy
  - ○ Energy loss through **ionisation / excitation** of the medium

Shower development

- High energy particle creates a **cascade** of lower energy electrons and photons
  - Through bremsstrahlung and pair production
- When the **critical energy** is reached, secondary particles are slowly **stopped** (electrons) or **absorbed** (photons)



Energy loss and mean free path

Two dominant processes: Bremsstrahlung and pair production

Electron energy loss

$$-\left(\frac{dE}{dx}\right)_{rad}=\frac{E}{X_0}$$

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

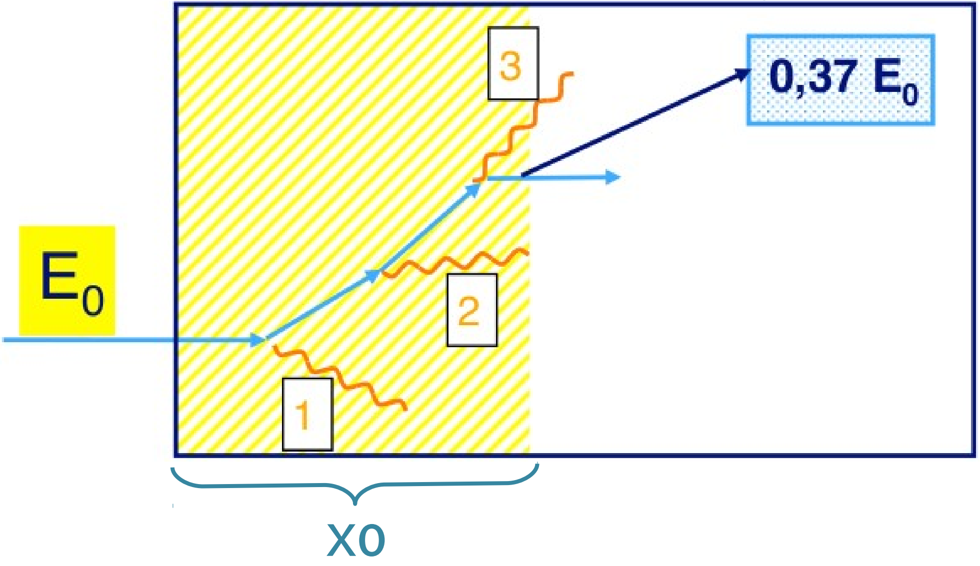
$$x(E_0/2)=X_0\ln(2)$$

Pair prod. probability

$$\frac{dw}{dx}=\frac{1}{\lambda_{pair}}e^{-x/\lambda_{pair}}$$

$$\lambda_{pair}=\frac{9}{7}X_0$$

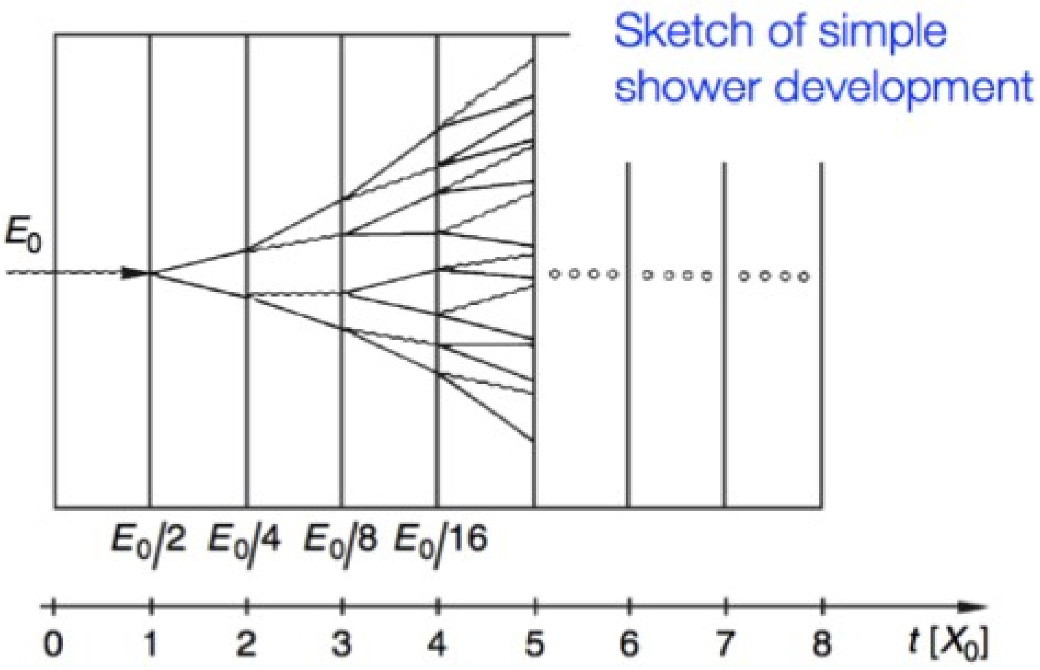
Radiation length X_0



- $X_0\approx\frac{180\,A}{Z^2}g.cm^{-2}$
- X_0 expressed in **cm or g.cm^{-2}**
  - ○ Conversion between the two with the material density
- Electrons loose half of their energy in about **$2/3\times X_0$**
- Photons convert in about **$9/7\times X_0$**

Simplistic shower model

- $x(E_0/2) = X_0 \ln(2)$ and $\lambda_{pair} = \frac{9}{7} X_0$, and the average roughly equals to X_0
- So we consider that, on average
  - One **particle duplication occurs every X_0** ($e \rightarrow e\gamma$ or $\gamma \rightarrow ee$)
  - With **equal sharing of energy** between the two produced particles
- Stops at the critical energy **$E = E_c$**
  - Reaches **maximum number of particles** = "shower maximum"



$t = x / X_0$

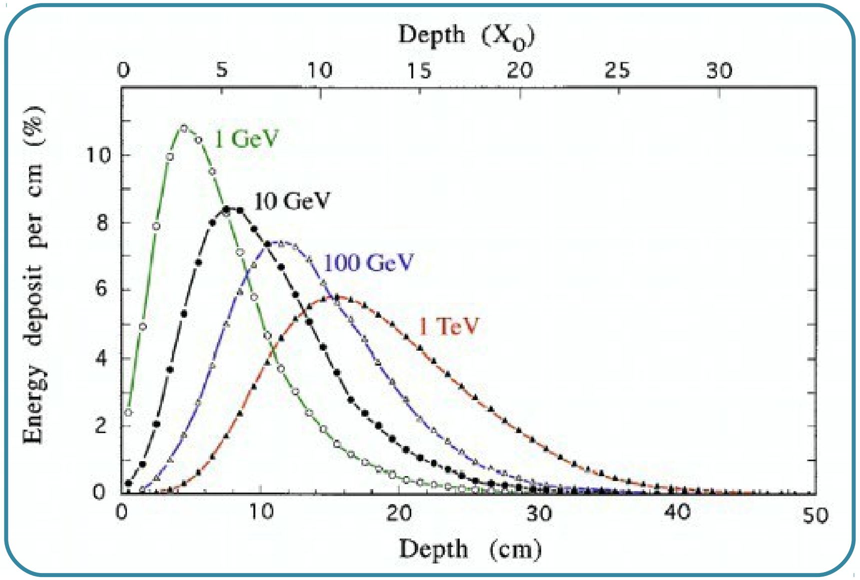
Some EM shower properties

- Number of particles proportional to the initial energy
  - Energy per particle after depth t: $E = E_0 \cdot 2^{-t}$
  - Shower maximum $t_{max} \propto \ln\left(E_0 / E_c\right)$ (X_0 units)
- Shower lateral extent
  - **Narrow core**
    - Early stage of the shower
    - 90% of shower contained in **"Moliere" radius**

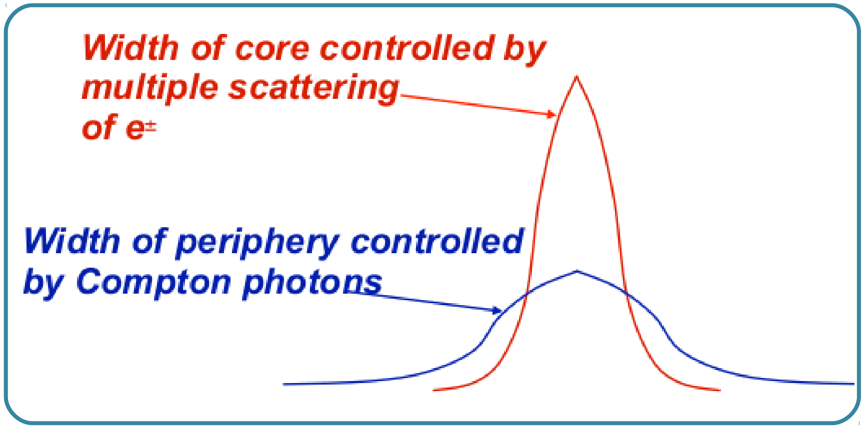
$$R_M = \frac{21\, MeV \times X_0}{E_c} \approx \frac{7\, A}{Z}\, g.cm^{-2}$$

  - **Tails at larger angles**
    - Isotropic Compton scattering
    - Beyond shower max

Longitudinal profile



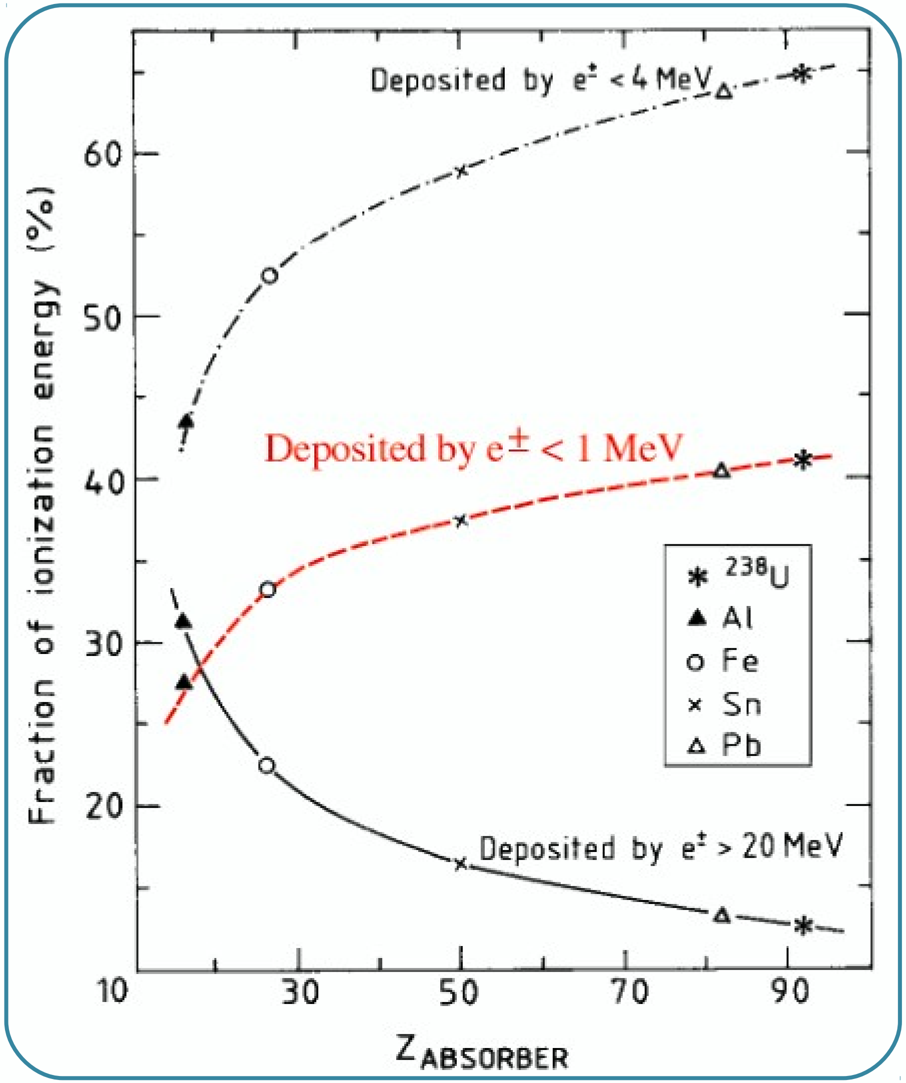
Lateral profile



Importance of low energy particles

- Shower development driven by high-energy particles
- But phenomena at **$E < E_c$ are important for calorimeter** properties
  - In lead 40% of the energy deposited by electrons < 1MeV

Fractions of deposited energy for 10 GeV EM showers



Useful quantities

- **Critical energy**
  for solids & liquids

$$E_c = \frac{610\,MeV}{Z+1.24}$$

- Critical energy
  for gaz

$$E_c = \frac{710\,MeV}{Z+0.92}$$

- **Radiation length**
  (approximate formulas)

$$X_0 \approx \frac{180\,A}{Z^2}\,g.cm^{-2}$$

$$X_0 \approx \frac{716.4\,A}{Z(Z+1)\ln(287/\sqrt{Z})}\,g.cm^{-2}$$

Compound:

$$\frac{1}{X_0} = \sum \frac{m_j}{X_j}$$

m_j = fraction of material by mass
X in $g.cm^{-2}$

Mixture:

$$\frac{1}{X_0} = \sum \frac{v_j}{X_j}$$

v_j = fraction of material by volume
X in cm

- **Shower maximum**
  (X_0 units)

$$t_{max} = \ln(E_0/E_c) - \begin{matrix} 1 & \text{(electrons)} \\ 0.5 & \text{(photons)} \end{matrix}$$

- 95% longitudinal containment
  (X_0 units)

$$L(95\%)/X_0 = t_{max} + 0.08\,Z + 9.6$$

- **Moliere radius**
  (same as X_0 for compound/mixture)

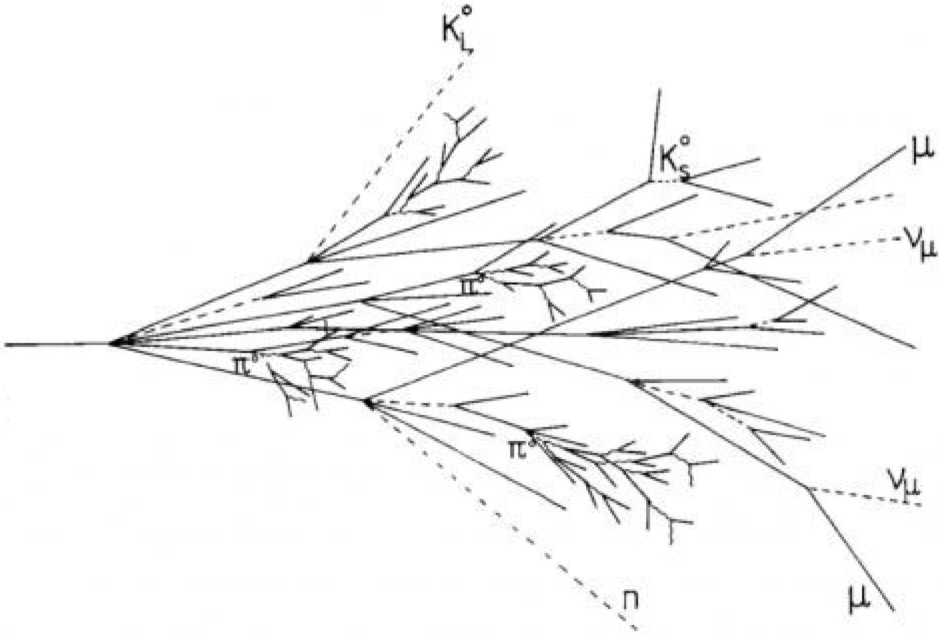
$$R_M = \frac{21\,MeV \times X_0}{E_c} \approx \frac{7\,A}{Z}\,g.cm^{-2}$$

- 95% lateral containment

$$R(95\%) = 2\,R_M$$

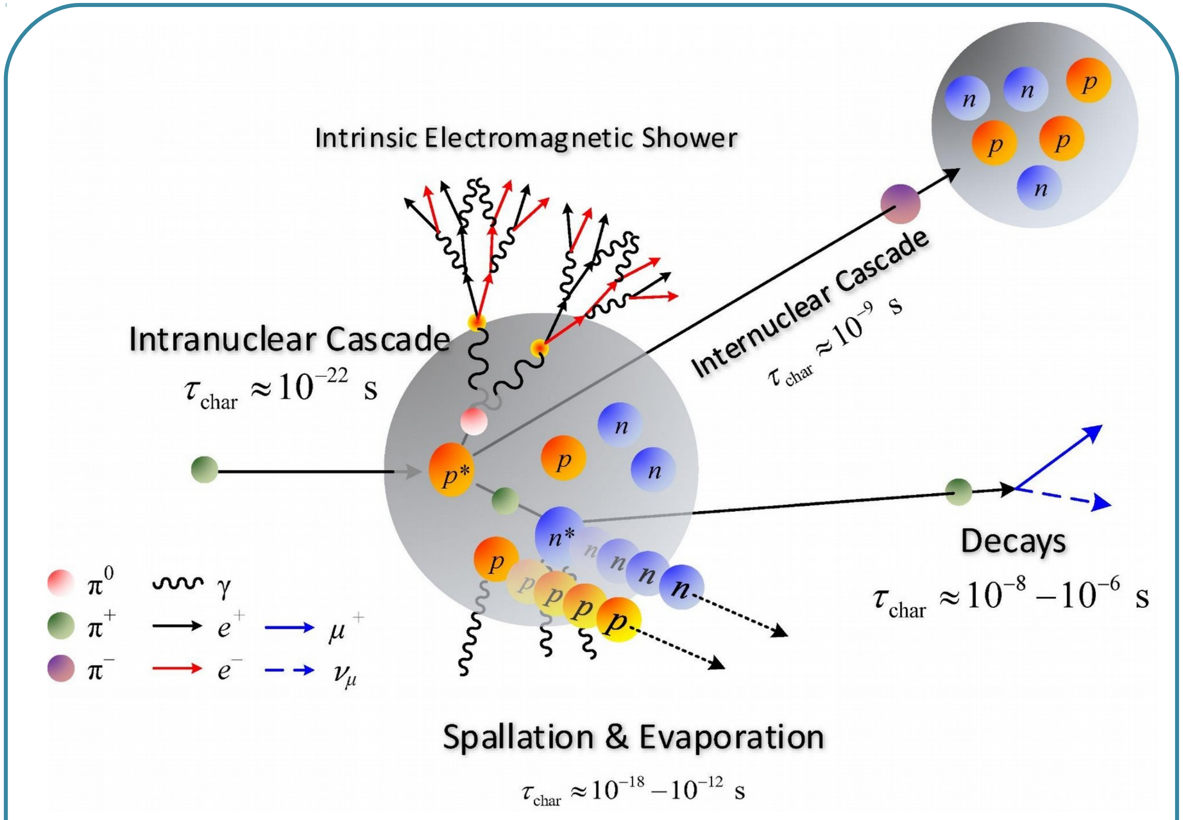
Hadronic showers

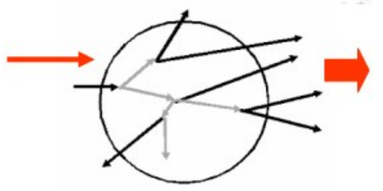
- Cascade of particles **initiated by a hadron**
  - Strong interaction in addition to EM interaction
- **Many processes** involved
  - Ionisation
  - Hadron production (fragmentation, etc.)
  - Charge exchange
    - $\pi\, n \rightarrow \pi^0\, p$
  - Spallation, fission
  - Nuclear de-excitation
  - Pion decay
  - …



Hadronic interactions

Hadronic shower evolution

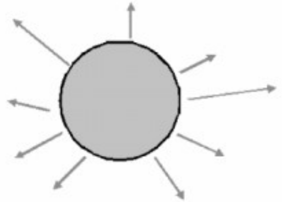




Intranuclear cascade

Incoming direction

Fast



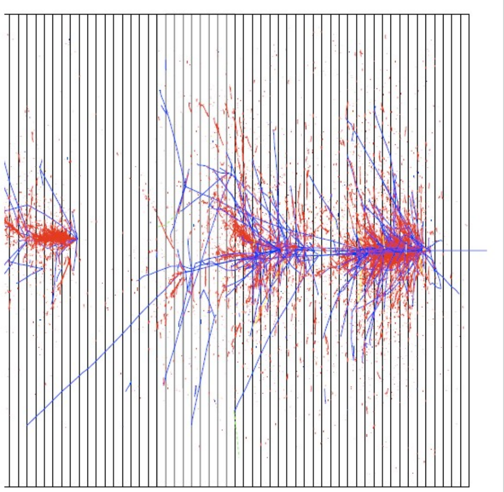
Evaporation

Isotropic

Slow

- 1) **Hard collision**
  - ○ Can travel long distance before 1st interaction
  - ○ Similar to a MIP
- 2) **Spallation**
  - ○ Intra-nuclear cascade
  - ○ Frees protons and neutrons
  - ○ Nucleus excitation and de-excitation (evaporation)

"Typical" hadronic shower



Electromagnetic component

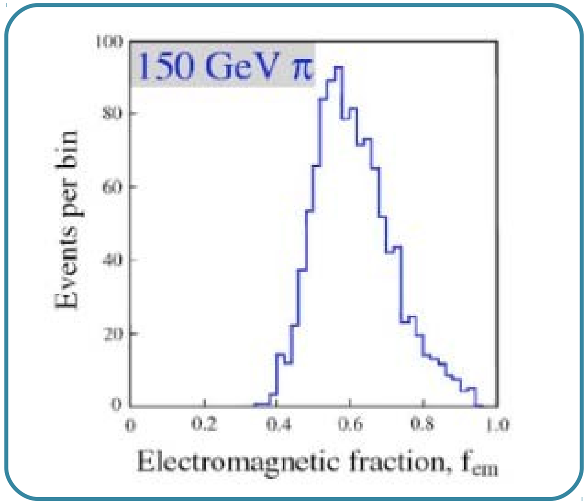
- Contributions
  - ○ Electrons & photons
  - ○ **Neutral pions** (e.g. $\pi^0 \to \gamma\gamma$)
- About 1/3 of π^0 produced at each nuclear interaction
- On average, **EM fraction increases with energy**

$$\langle f_{em}\rangle = \langle E_{EM}/E_{tot}\rangle = 1-(E/E_0)^{k-1}$$

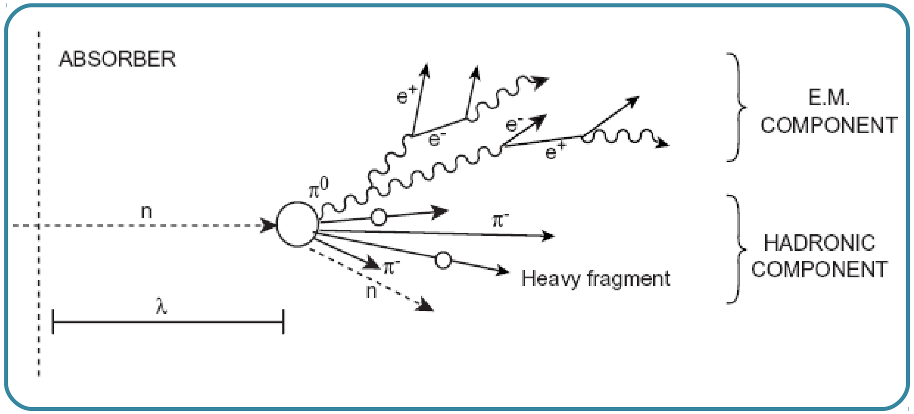
E_0 = average energy needed for π^0 production

k is related to the average multiplicity of π^0 produced at each interaction

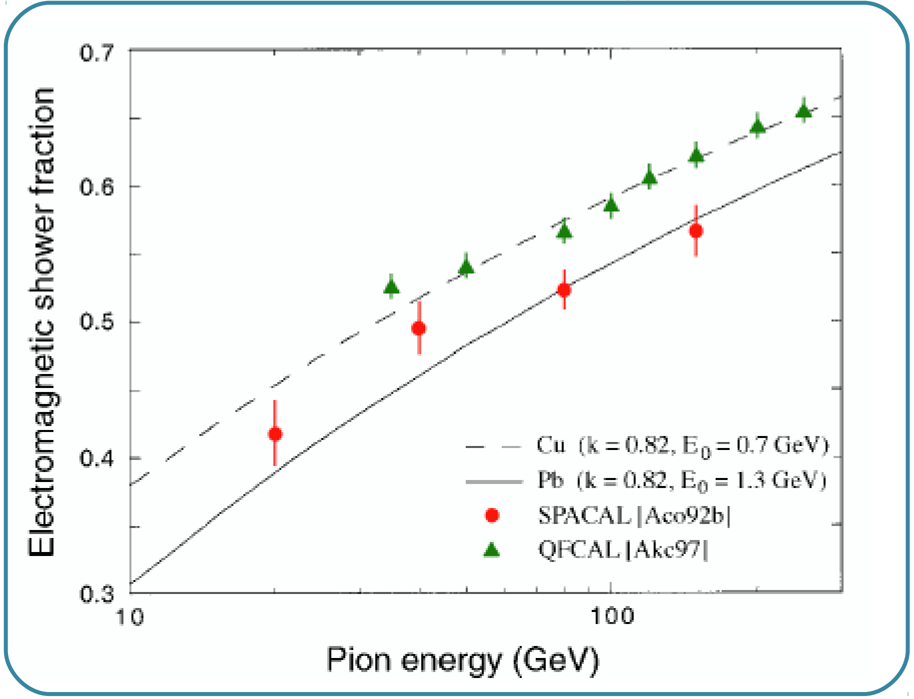
Fluctuations in EM fraction



First hadronic interaction



EM fraction vs energy



Non-EM components

Non-EM energy breakdown

Numbers for Lead

56% ionizing particles

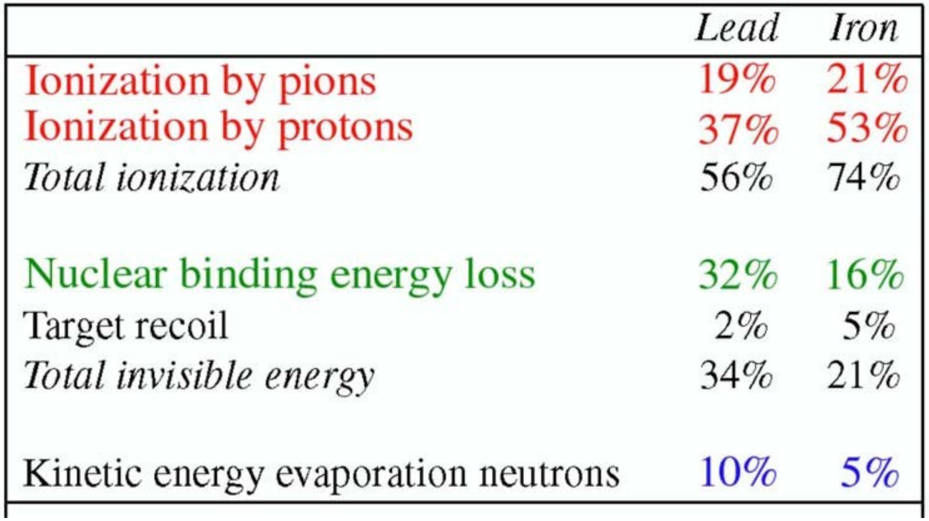
2/3 are protons (from spallation)
<E> ~ 50-100 MeV

34% invisible

Break-up of nuclei

10% neutrons

Very soft (typically a few MeV)
On average 37n per deposited GeV



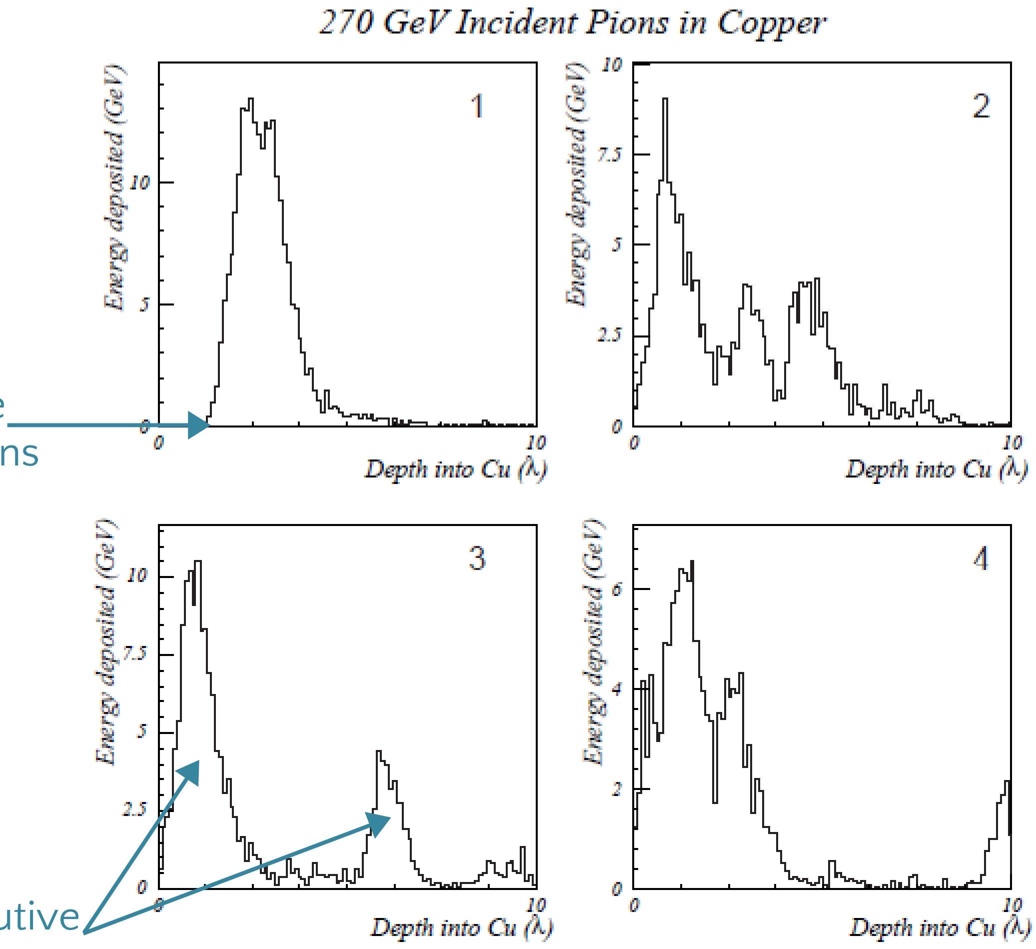
	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%

- A large part of energy losses is **invisible**
  - Energy used to release protons and neutrons from nuclei
  - Kinetic energy carried by recoil nuclei
- Also significant fraction in **evaporation neutrons**
  - Elastic scattering (large energy transfer for small nuclei, e.g. Hydrogen)
  - Neutron capture (sizeable energy, but late w.r.t. main shower component)

Shower development

- A hadronic shower doesn't have a profile which can be parameterized
- The size of the 1st interaction will essentially determine the EM fraction

Examples of longitudinal development



A pion can travel a significant distance before the first interaction happens

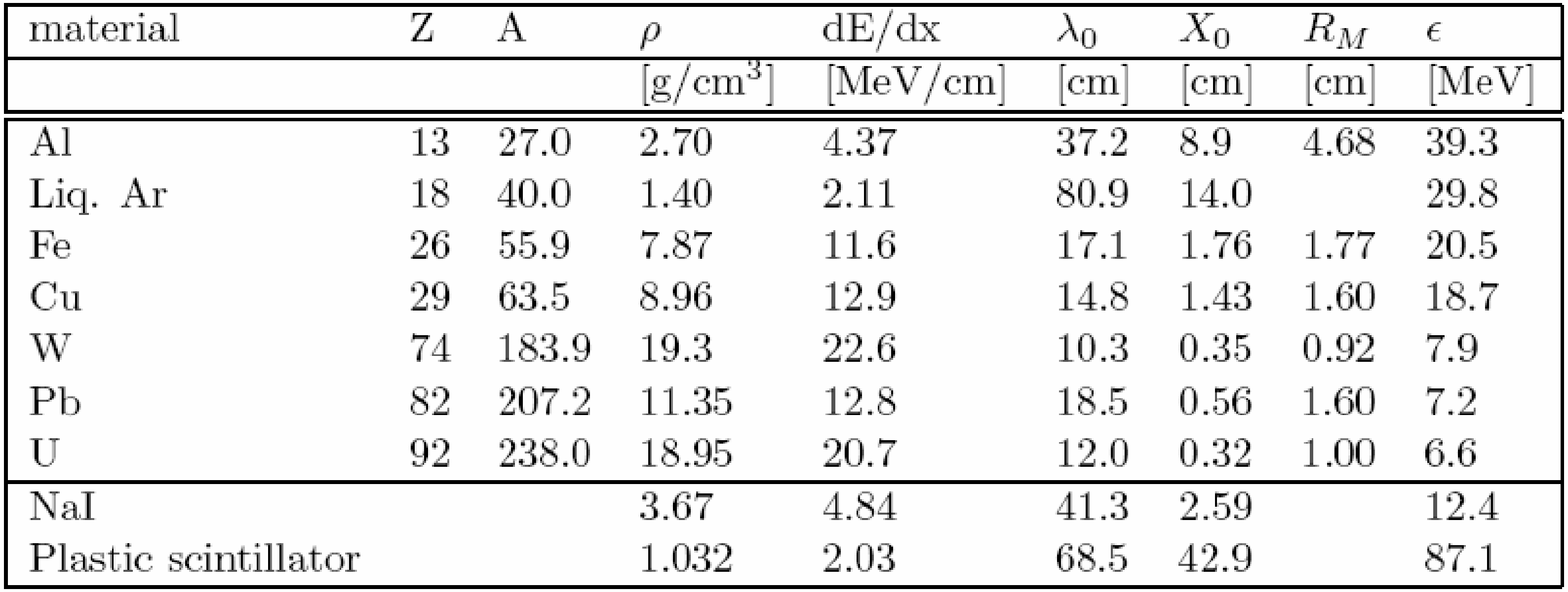
π_0 production in consecutive hadronic interactions

Exercises

- In the next two slides are a few exercises related to EM showers
- The solutions can be found on the ESIPAP Indico page

EM shower development in lead and iron

- Where is the shower maximum, in numbers of X_0, for:
  - ○ A 100 GeV electron in lead?
  - ○ A 1 TeV photon in lead?
  - ○ A 100 GeV electron in iron?
  - ○ A 1 TeV photon in iron?
- How many cm of Pb or Fe are needed to stop (meaning a loss of 95% of their energy) a 100 GeV electron? And a 1 TeV photon?
- For EM showers, is it better to have lead or iron?



material	Z	A	ρ	dE/dx	λ_0	X_0	R_M	ϵ
			[g/cm^3]	[MeV/cm]	[cm]	[cm]	[cm]	[MeV]
Al	13	27.0	2.70	4.37	37.2	8.9	4.68	39.3
Liq. Ar	18	40.0	1.40	2.11	80.9	14.0		29.8
Fe	26	55.9	7.87	11.6	17.1	1.76	1.77	20.5
Cu	29	63.5	8.96	12.9	14.8	1.43	1.60	18.7
W	74	183.9	19.3	22.6	10.3	0.35	0.92	7.9
Pb	82	207.2	11.35	12.8	18.5	0.56	1.60	7.2
U	92	238.0	18.95	20.7	12.0	0.32	1.00	6.6
NaI			3.67	4.84	41.3	2.59		12.4
Plastic scintillator			1.032	2.03	68.5	42.9		87.1

Properties of CsI crystal

Density: 4.51 g.cm^{-3}, Ec = 11.17 MeV

	Atomic Mass	X_0 (g.cm^{-2})	R_M(g.cm^{-2})
Cs	132.9	8.31	15.53
I	126.9	8.48	15.75

- CsI crystal
  - ○ Compute the radiation length of a CsI crystal (in g.cm^{-2})
  - ○ Give X_0 in cm
  - ○ What is its Moliere radius (g.cm^{-2} and cm)