Particle Interactions with Materials and Detection Mechanism

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Cloud Chamber

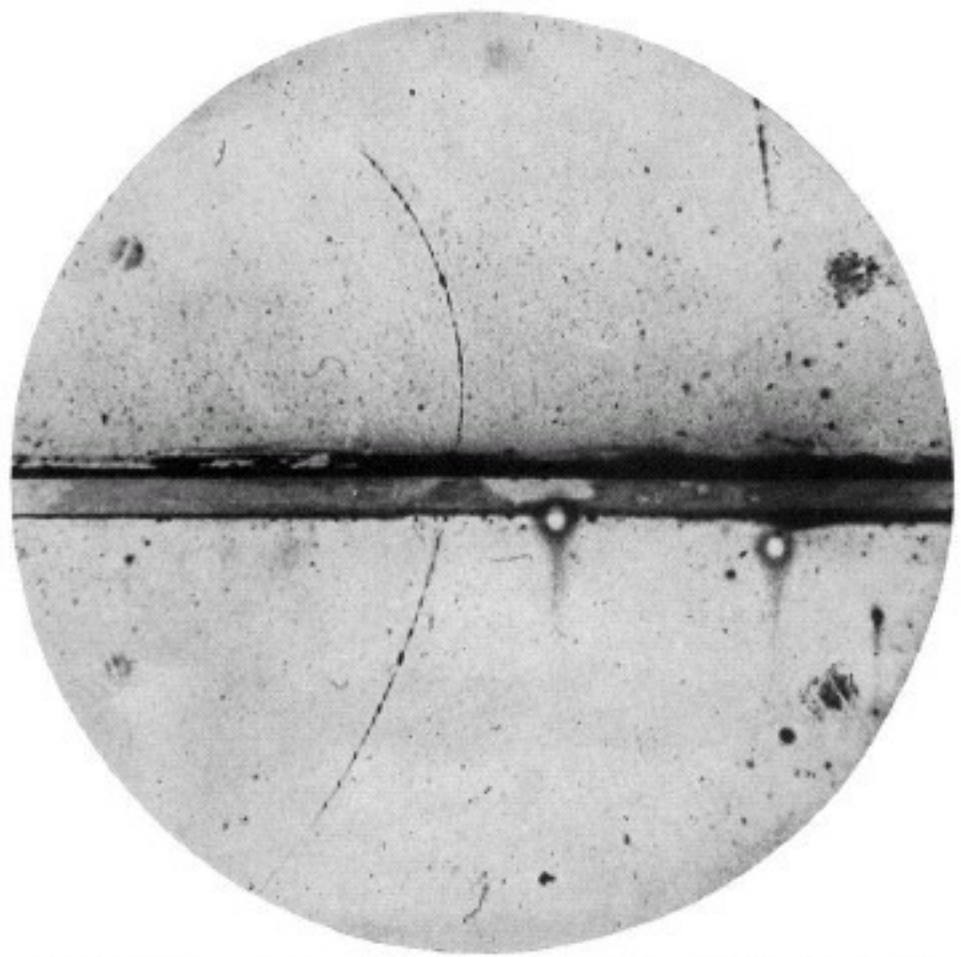
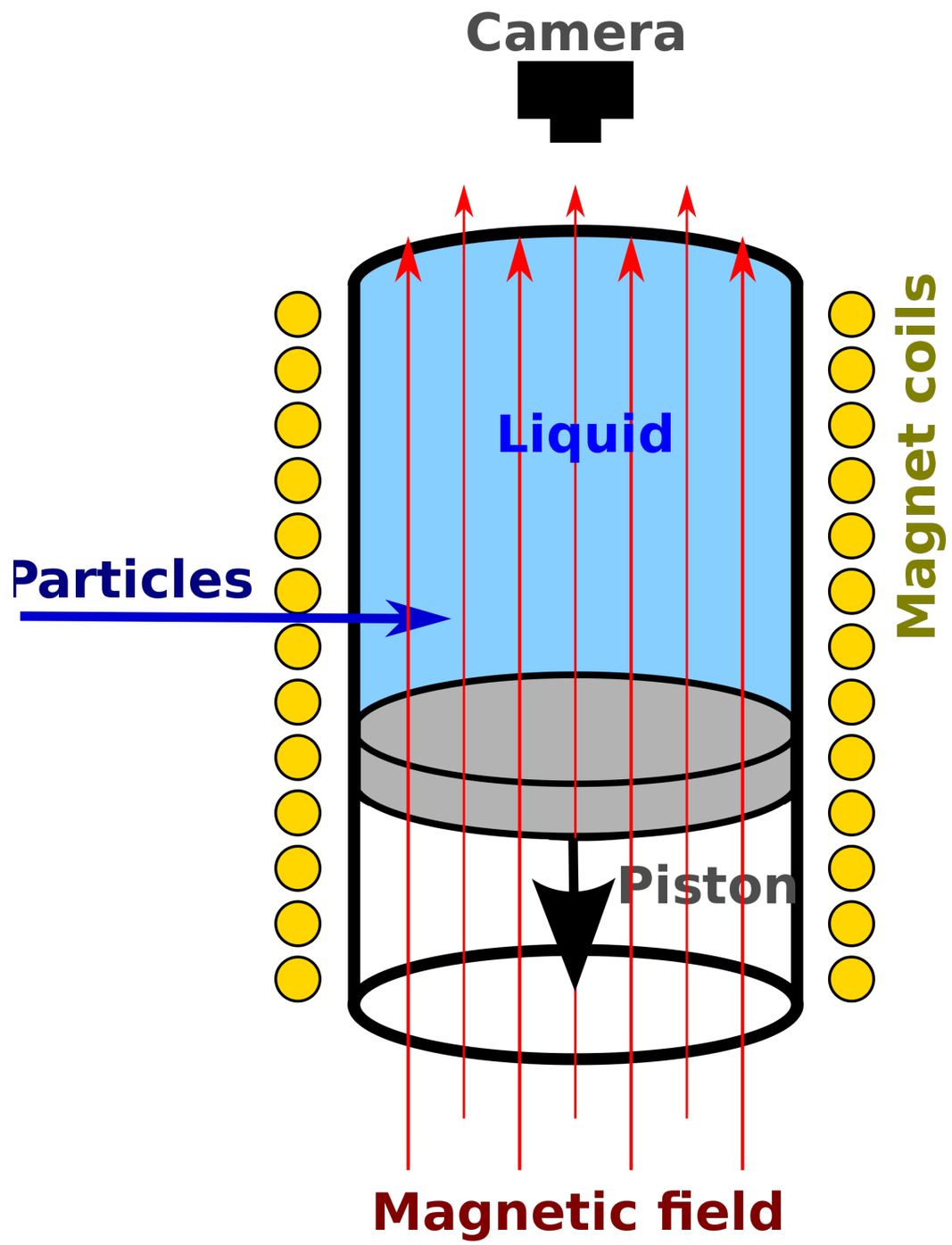
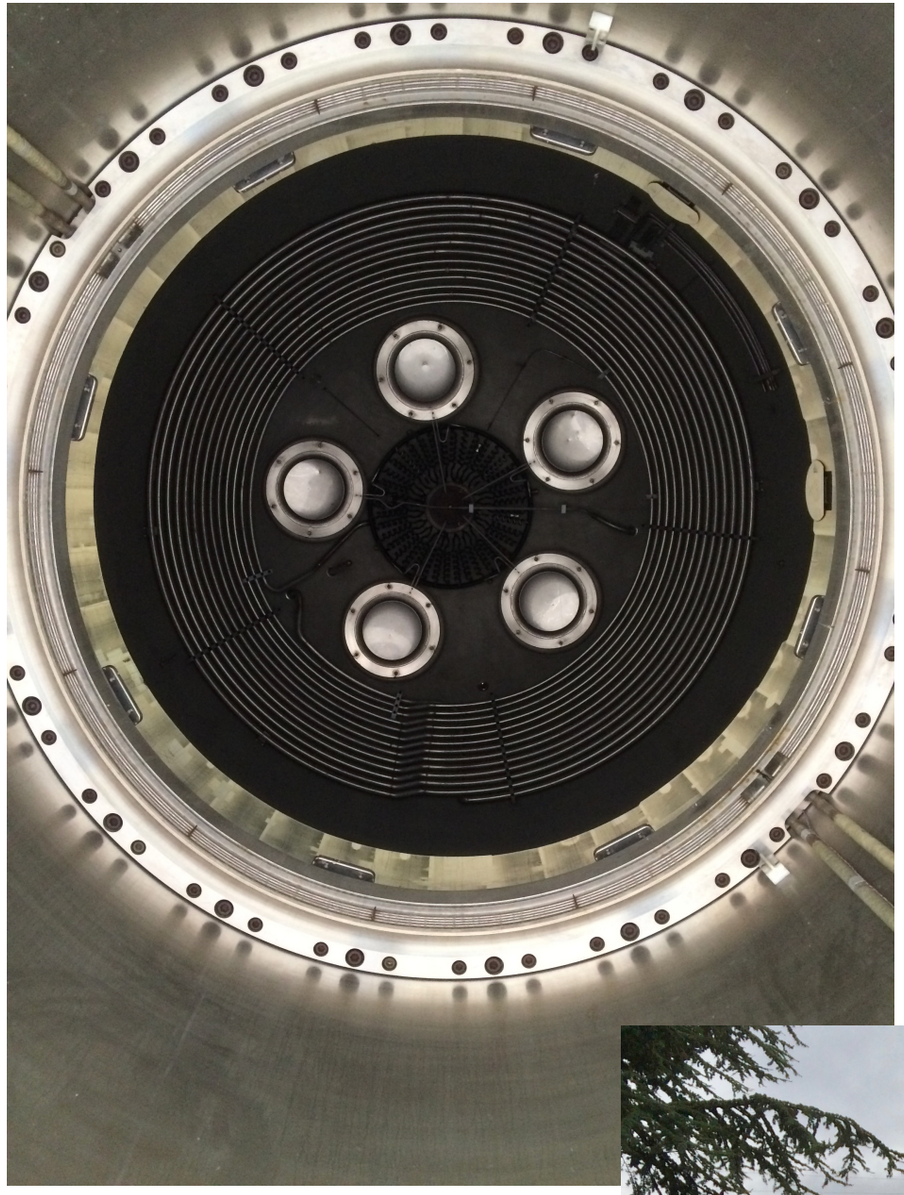


Figure 11.1: One of the first positron tracks observed by Anderson in his cloud chamber.

Bubble Chamber





Bubble Chamber

Bubble Chamber

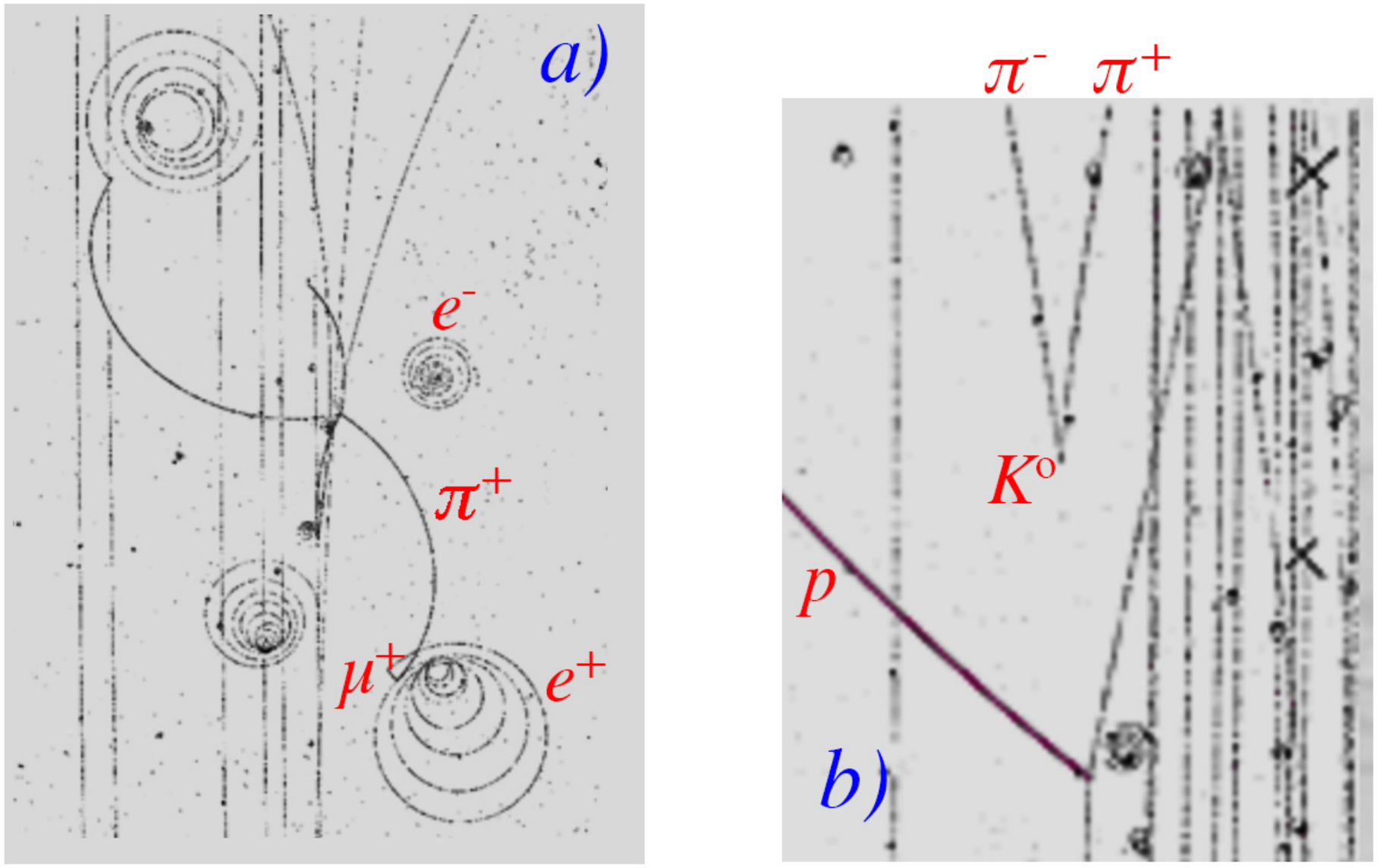
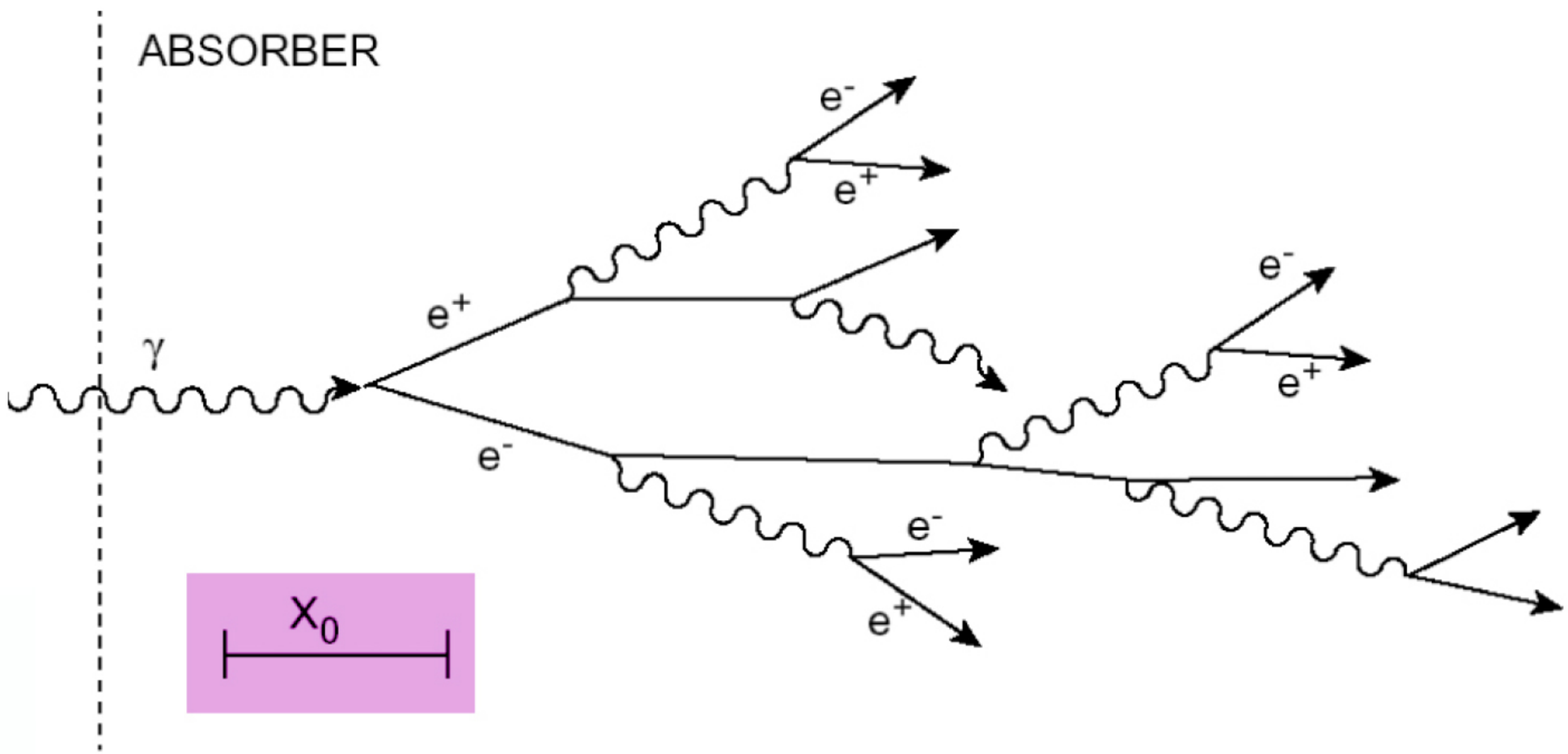


Figure 9.12: Examples of bubble chamber pictures in which noticeable events take place. The 2-meter hydrogen filled bubble chamber at CERN was exposed to a beam of K^-. In diagram a, the decay chain of a positive pion is visible ($\pi^+ \to \mu^+ \to e^+$). Diagram b shows the production of a neutral particle (K^0), that decays after a few cm into a $\pi^+\pi^-$ pair.

Electromagnetic Shower

Electromagnetic Shower



- Radiation length: the distance over which a high-energy (>> 1 GeV) *electron or positron* loses, on average, 63.2% of its energy to bremsstrahlung

Electromagnetic Shower

- **Energy loss by charged particles**
  - The particles **ionize** medium if their energy is sufficient to release the atomic electrons
  - Charged particles may excite atoms or molecules and the de-excitation from these metastable states may yield **scintillation** light
  - Charged particles traveling faster than the speed of light in the medium lose energy by emitting **Cerenkov light**
  - At high energies, energetic knock-on electrons (**δ-rays**)
  - At high energies, **bremsstrahlung**
  - At very high energies, the em interaction may induce **nuclear reactions**

Altogether, exact, in an infinite medium, the ionization energy loss (in MeV/g-cm^{-2}):

$$\frac{dE}{dx} = K\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Lorentz contraction of E field

ionization potential

maximum energy transfer to electron

polarization of the medium

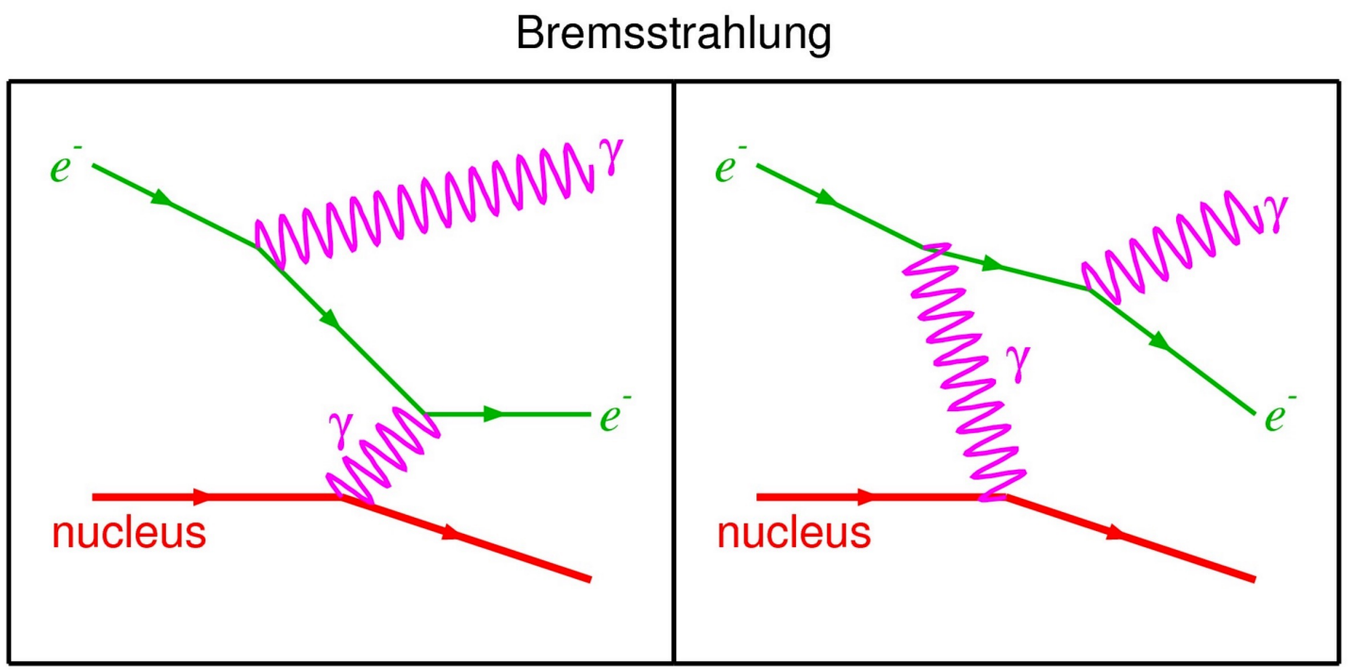
where $K = 4\pi N_A r_e^2 m_e c^2 = 0.307075 \text{ MeV / g·cm}^{-2}$

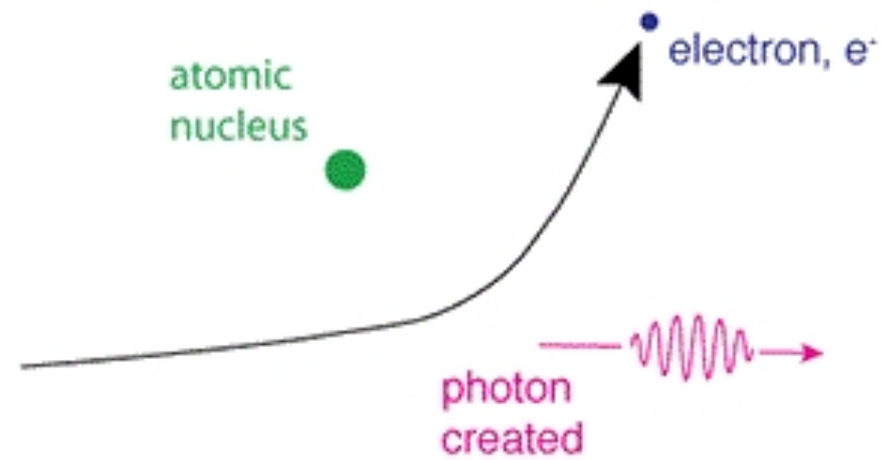
This elegant formula ("Bethe-Bloch") is seldom useful: finite media, B-field, δ-rays, UV, low-energy particles, …

Energy loss to nuclei is negligible ~ (m/M)

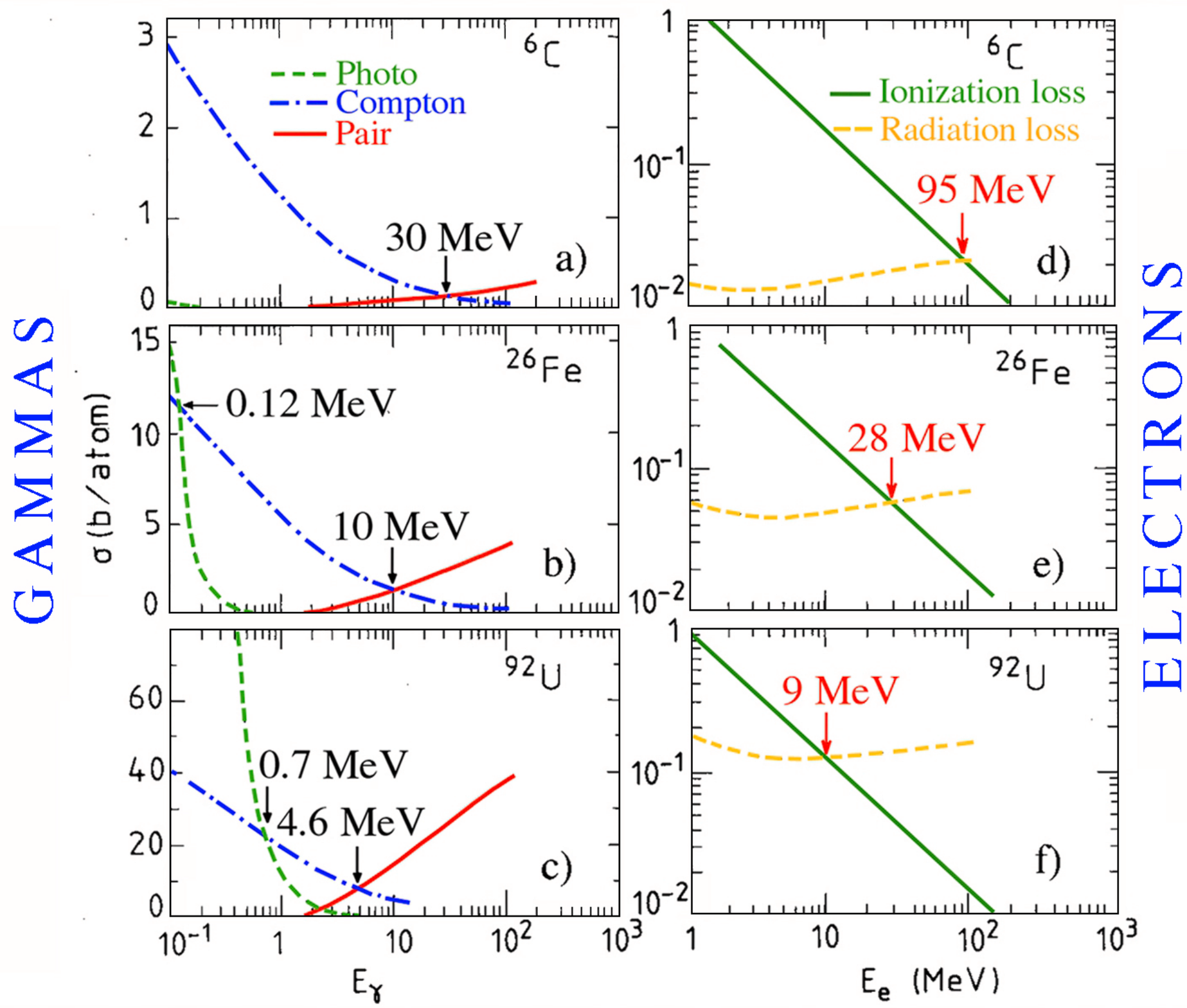
- Above 100 MeV and lower than that, the principle source of energy loss by electrons and positrons is **bremsstrahlung**.
  - **radiate photons** as a result of the Coulomb interaction with the electric fields generated by the atomic nuclei.
  - The **energy spectrum** falls off as **1/E**.
- The **critical energy** (energy losses by radiation process = energy losses by ionization) is higher by a factor $(m/m_e)^2$
  - The critical energy of muon is ~40000 times larger than that of the electron

Particle interactions with nuclei (Ze): bremsstrahlung ("braking radiation")





An electron radiates photons continuously, mostly low energy. On the average, the summed energy radiated in one radiation length is all but 1/e of the original electron energy.


GAMMAS
ELECTRONS
Photo
Compton
Pair
Ionization loss
Radiation loss
σ (b/atom)
E_γ
E_e (MeV)
^6C
^{26}Fe
^{92}U
30 MeV
0.12 MeV
10 MeV
0.7 MeV
4.6 MeV
95 MeV
28 MeV
9 MeV
a)
b)
c)
d)
e)
f)

Photon interactions

- **Photoelectric effect**, **Rayleigh scattering**, **Compton scattering**, **electron-positron pair production**

- **Photoelectric effect**

  - At low energies, an atom absorbs the photon and emits an electron.

  - cross section scales with $\mathbf{Z^n}$

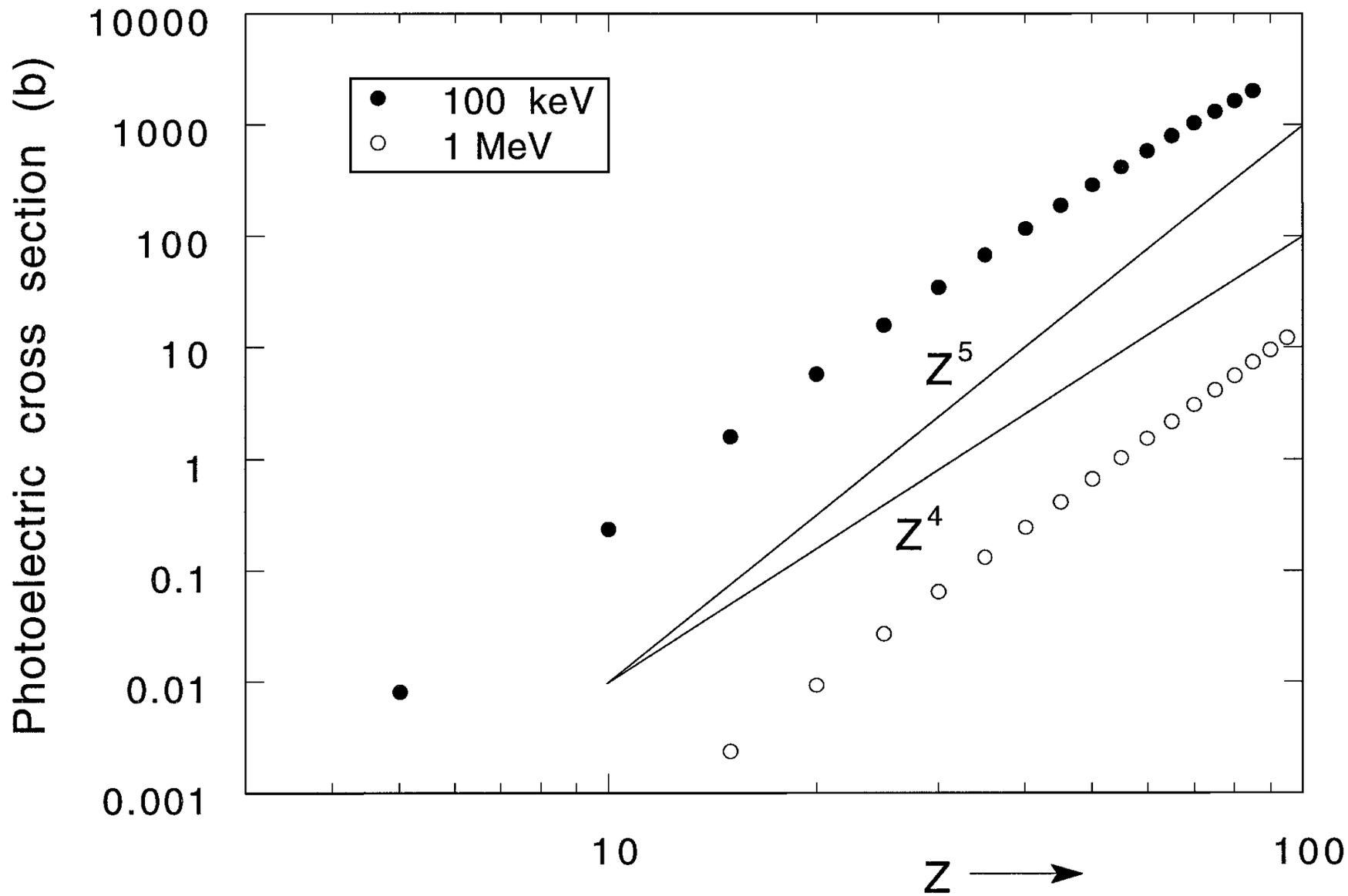
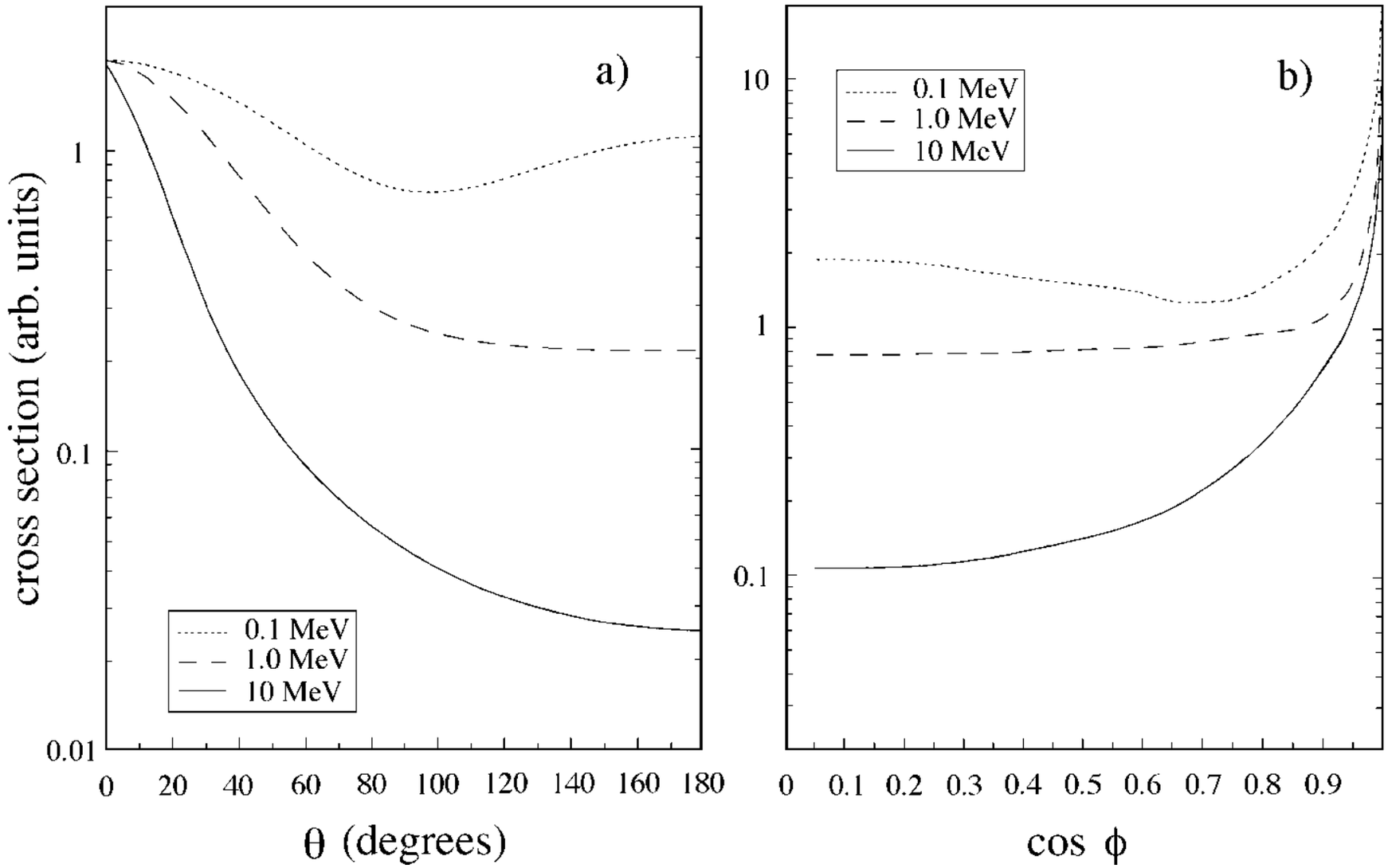
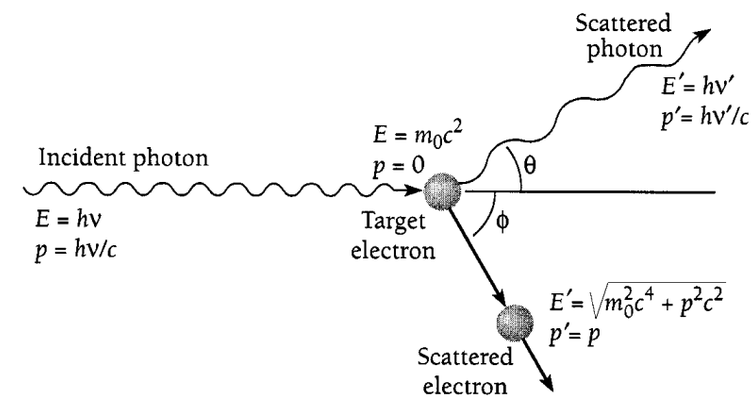


FIG. 2.3. Cross section for the photoelectric effect as a function of the Z value of the absorber. Data for 100 keV and 1 MeV γs.

- **Rayleigh scattering**
  - At low energies, the photon is **deflected by the atomic electrons**.
  - the photon **doesn’t loose energy**
  - doesn’t contribute to the energy deposition process
  - affect the **spatial distribution** of the energy deposition

- **Compton scattering**
  - a photon is **scattered by an atomic electron**
  - **momentum and energy are transferred** to the struck electron
  - as a result, this **electron** is put in an **unbound state**
  - γs in the energy range between **a few hundred keV and ~ 5 MeV**





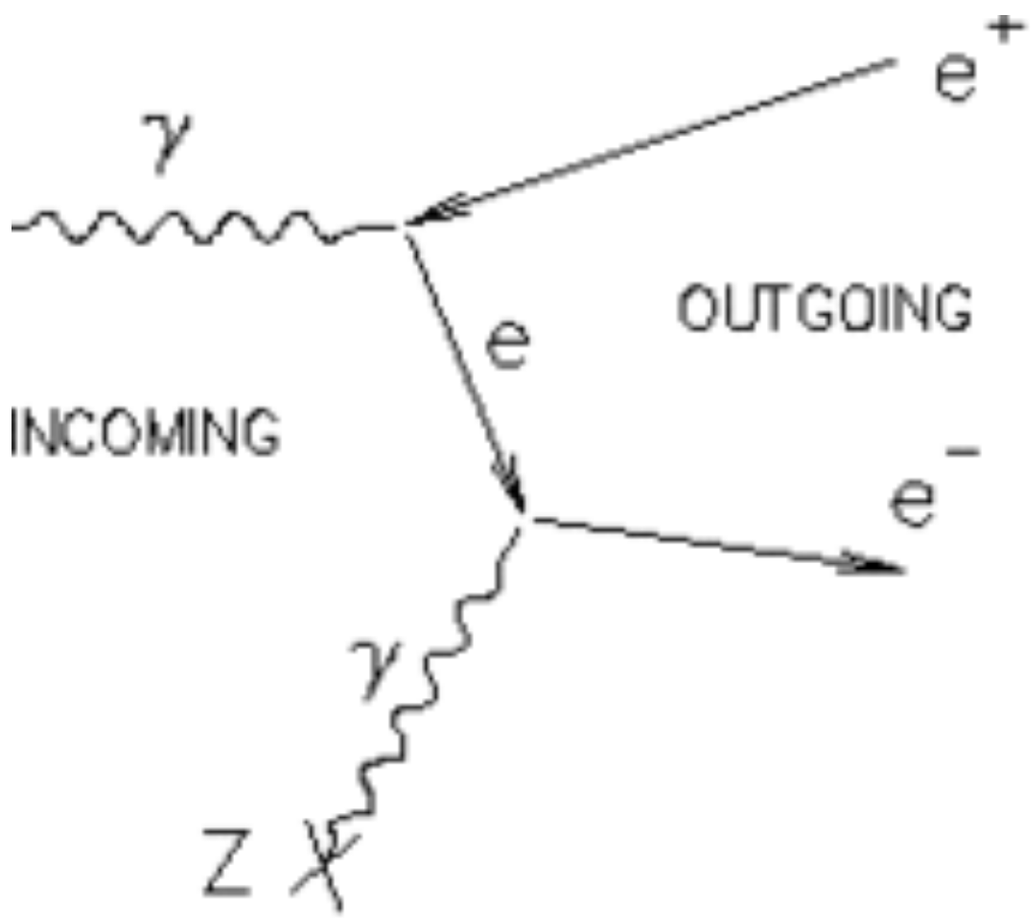
ϕ: electron scattering angle

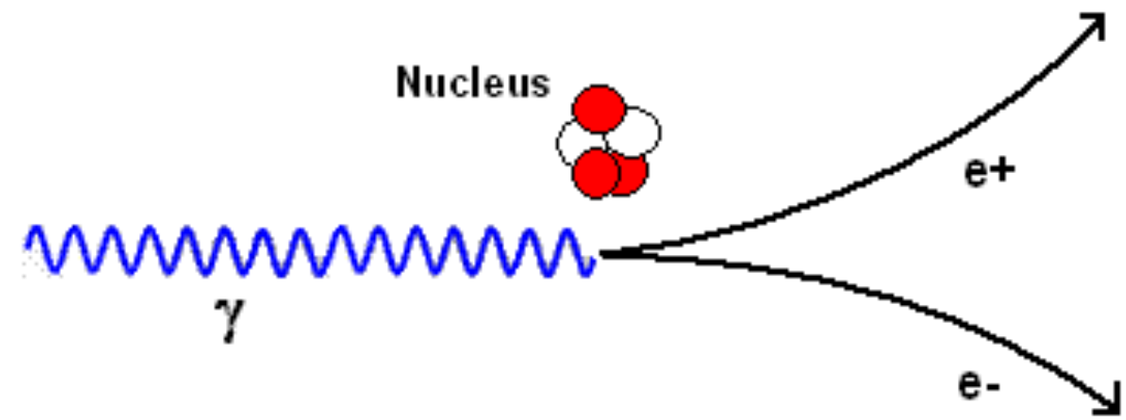
θ: photon scattering angle

FIG. 2.5. The cross section for Compton scattering as a function of the scattering angle of the photon (*a*), and the the angular distribution of the Compton recoil electrons (*b*), for incident photons of different energies.

- **Pair production**
  - energies **larger than twice the electron rest mass**
  - photon creates an **electron-positron pair**
  - electrons and positrons produce bremsstrahlung radiation as well as ionization along their paths
  - electron: eventually absorbed by an ion, positron: annihilates with an electron
  - more than 99% of the $\gamma \rightarrow e^+e^-$ are caused by **nuclear electromagnetic fields**.
    - For **low-Z elements and at high energies**: **the fields of the atomic electrons** also contributes significantly to the total pair production cross section

Particle interactions with nuclei (Ze): pair production





The photon penetrates 9/7 of a radiation length, on the average, before undergoing pair-production.

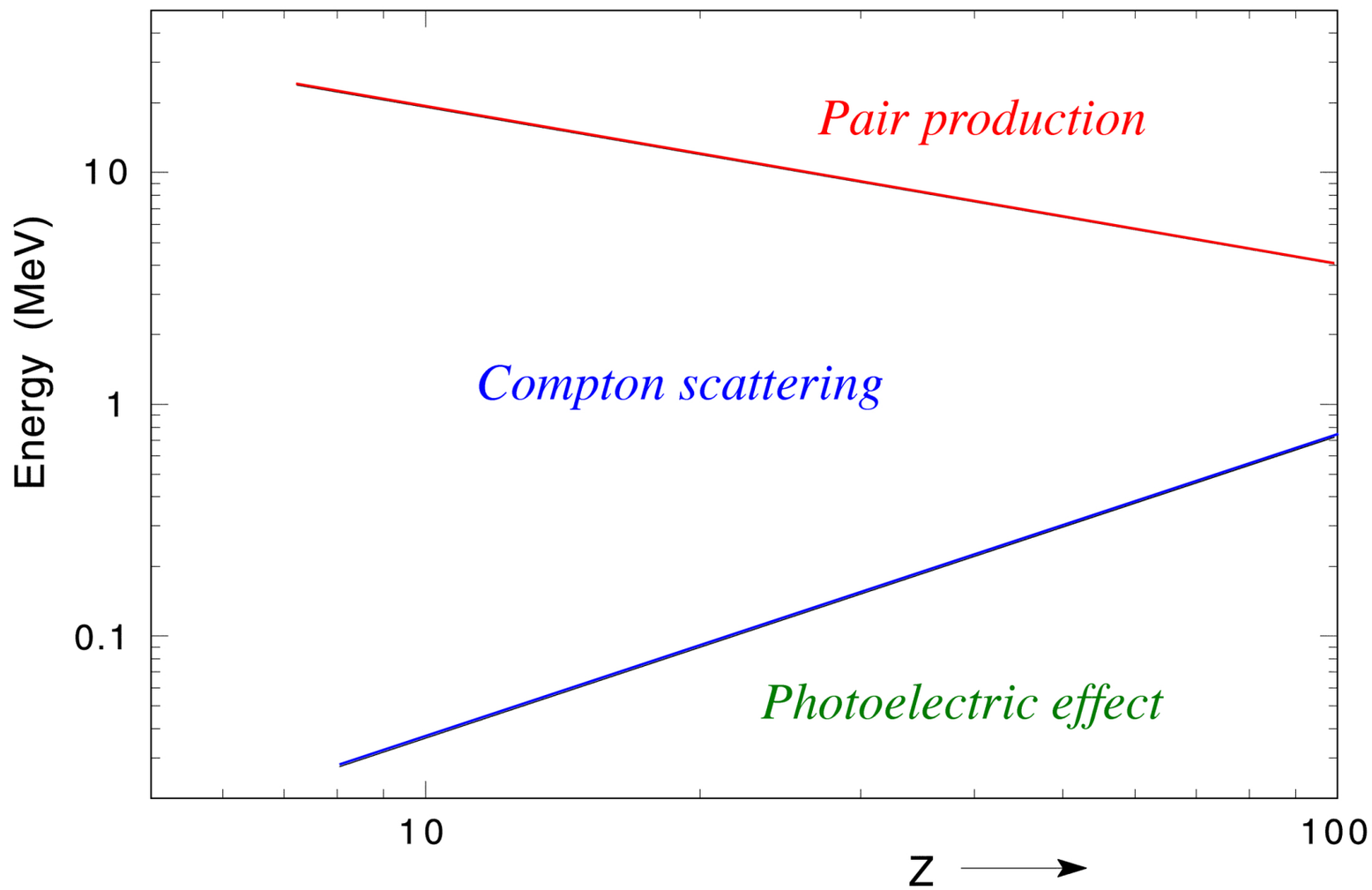


FIG. 2.7. The energy domains in which photoelectric effect, Compton scattering and pair production are the most likely processes to occur, as a function of the Z value of the absorber material.

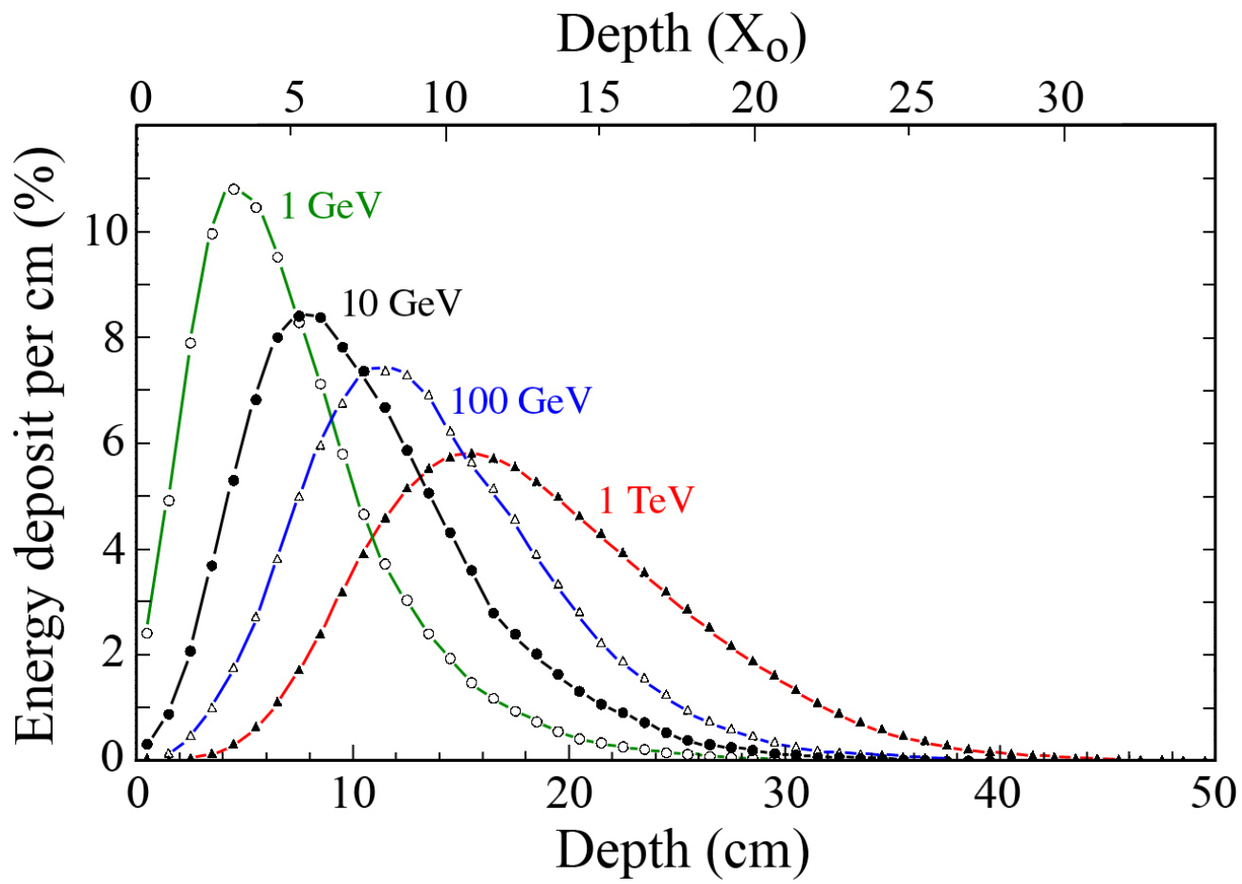


FIG. 2.9. The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalized to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 calculations.

- The higher the initial energy of the shower particle, the longer the particle multiplication phase continues
- The amount of copper needed to absorb 99% of shower energy: 23 cm at 1 GeV, 28 cm at 10 GeV, 33 cm at 100 GeV, 39 cm at 1 TeV

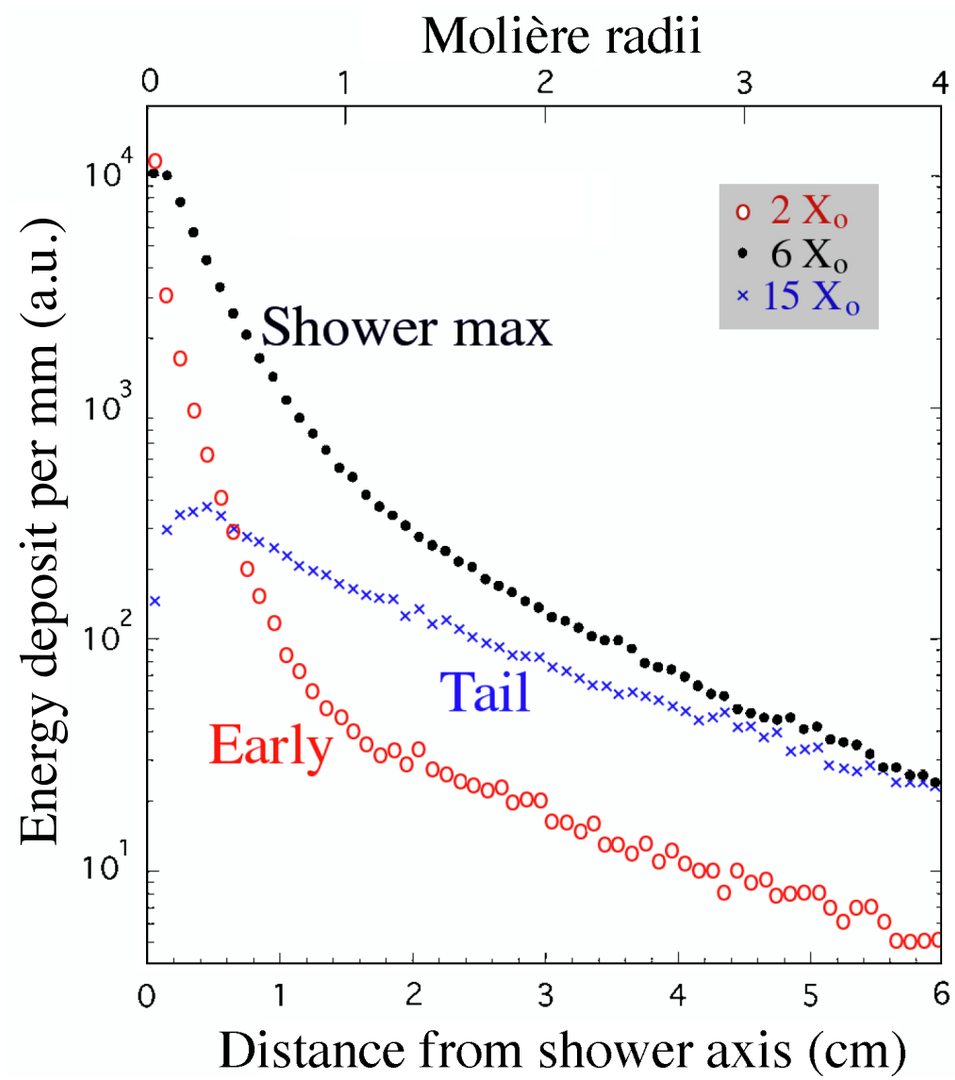
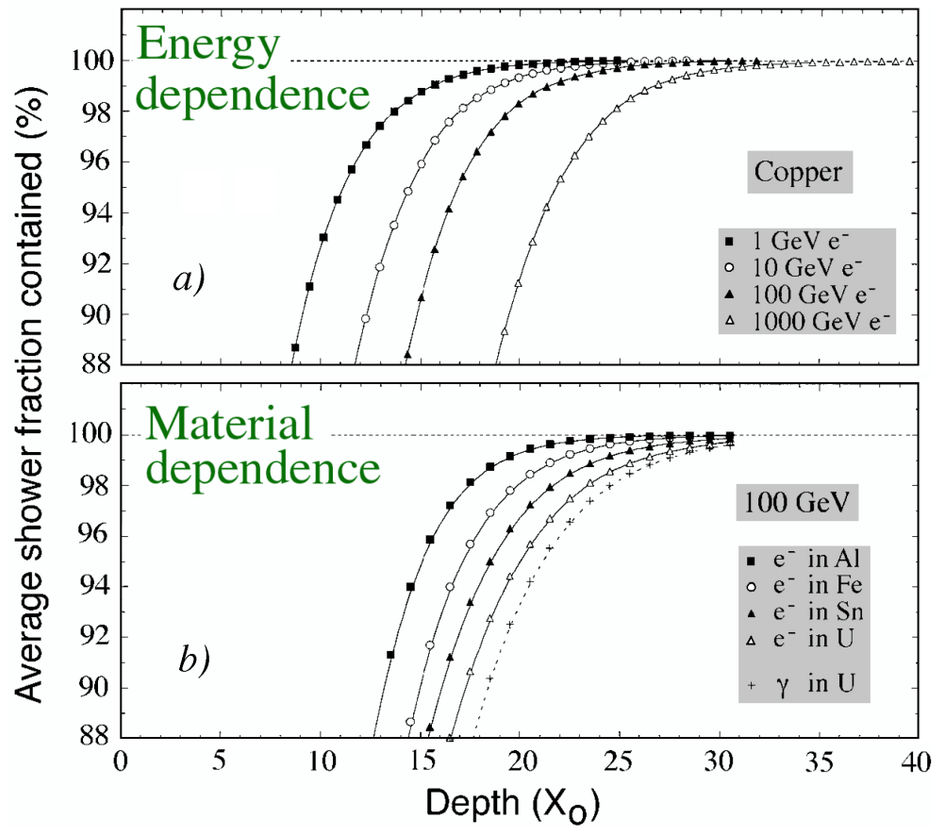


FIG. 2.13. The radial distributions of the energy deposited by 10 GeV electron showers in copper, at various depths. Results of EGS4 calculations.

- the central core (the first component), surrounded by a halo (the second component)

- the central core disappears beyond the shower maximum (15 X_0)

Shower Containment



- Shower containment is important since shower particles escaping from the detector becomes a source of fluctuations that my affect the precision of the measurements

- The absorber thickness:

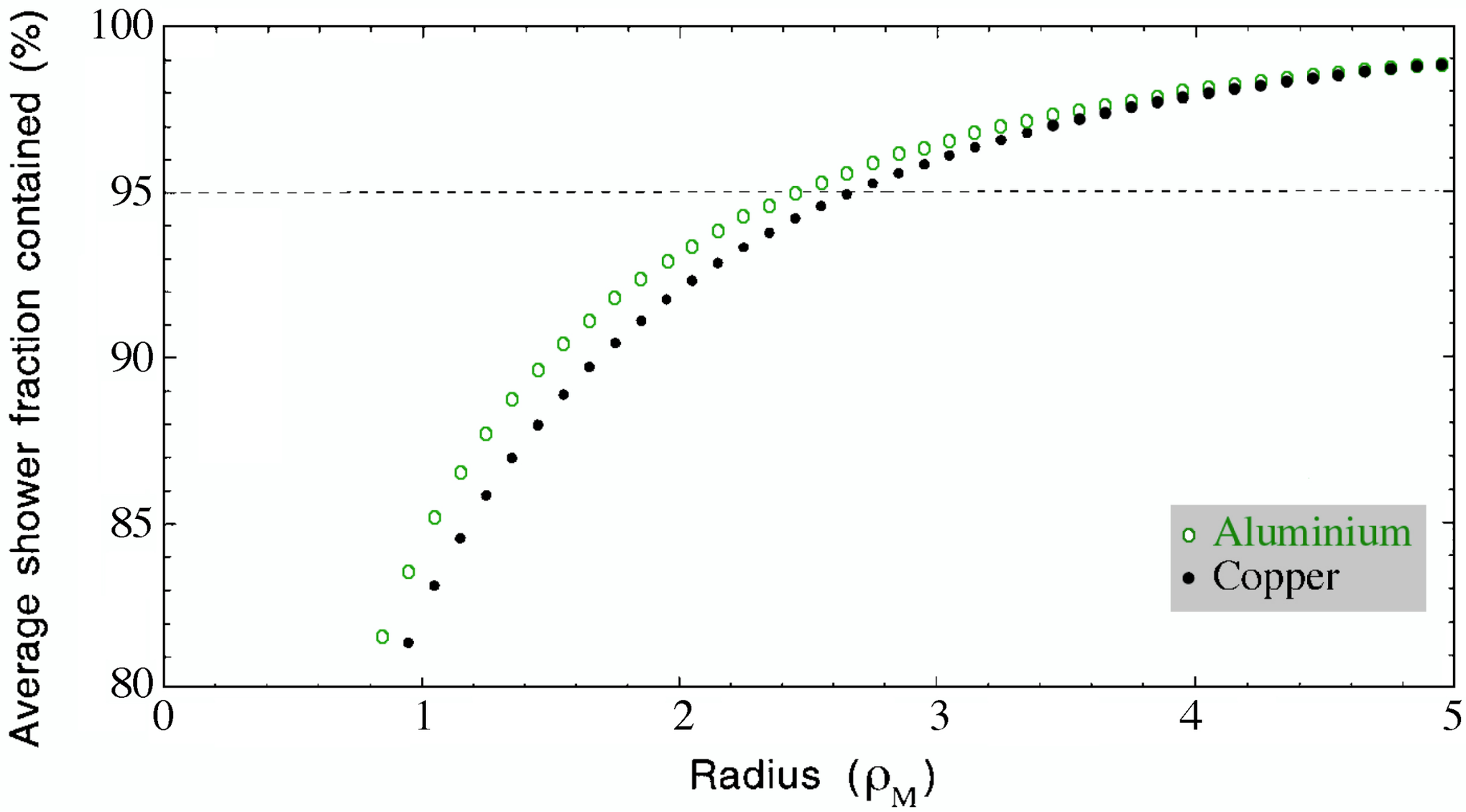
  - 11 X_0 at 1 GeV, 22 X_0 at 1 TeV (for 95% shower containment)

  - 16 X_0 at 1 GeV, 27 X_0 at 1 TeV (for 99% shower containment)

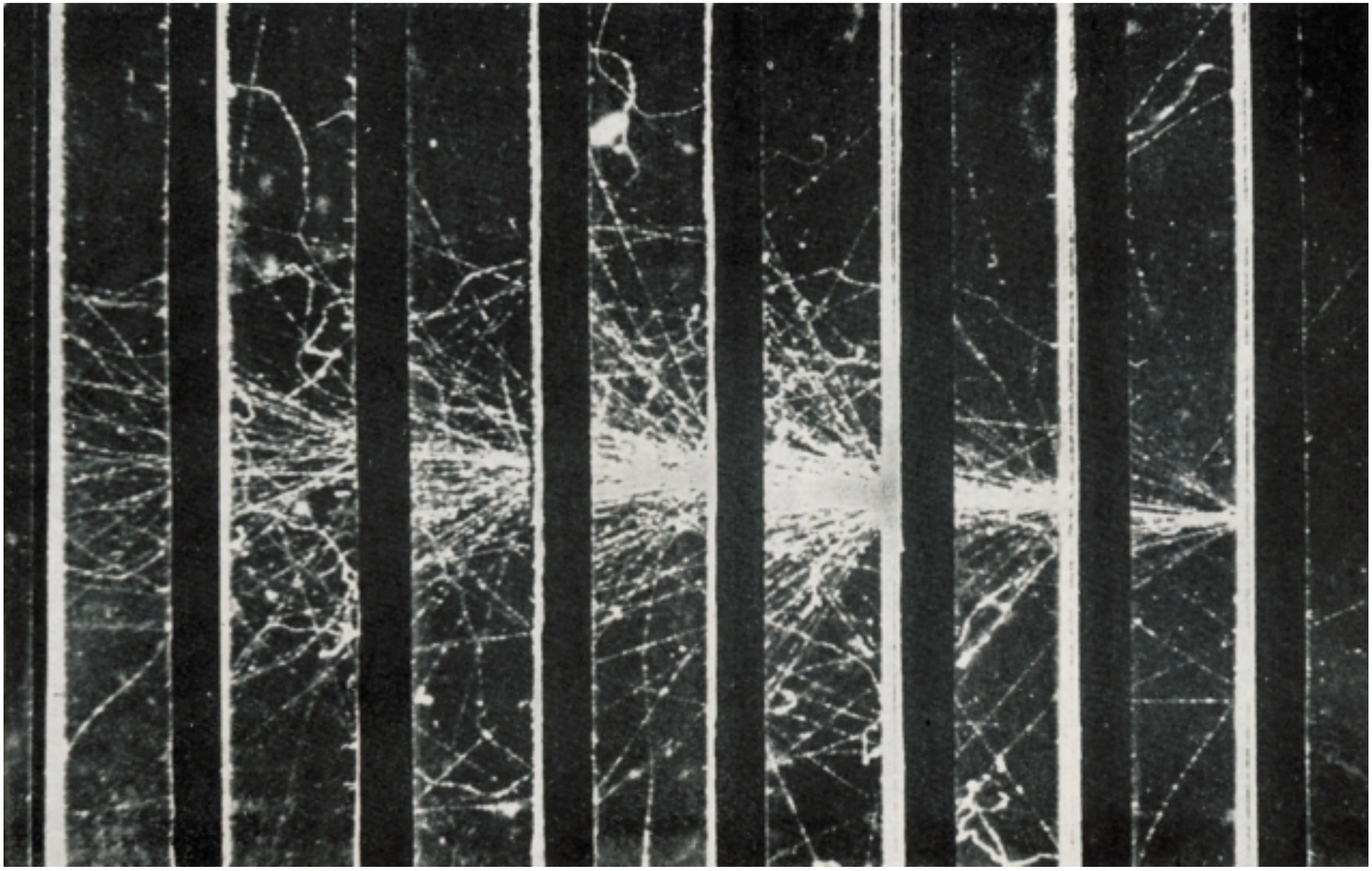
  - 19 X_0 of Al at 100 GeV, 26 X_0 for uranium at 100 GeV

  - γ-induced showers require 1 X_0 more material than

Shower containment

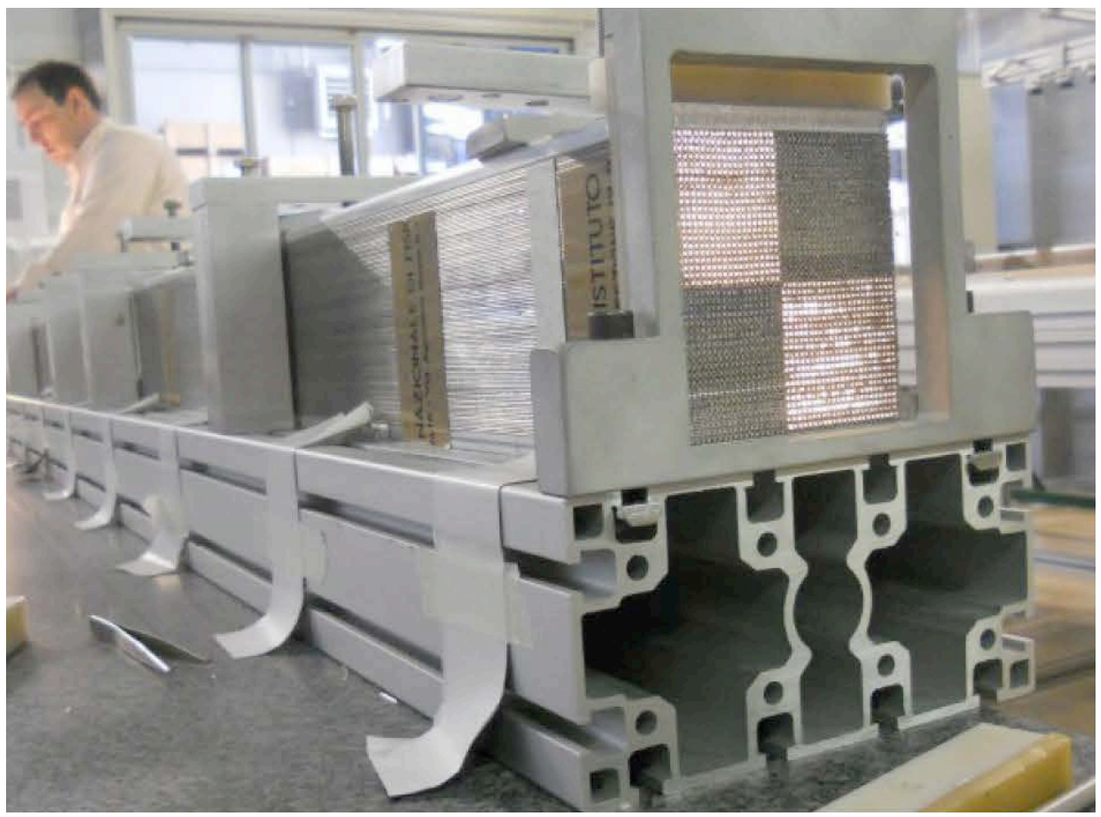


Electromagnetic shower initiated by a high energy electron

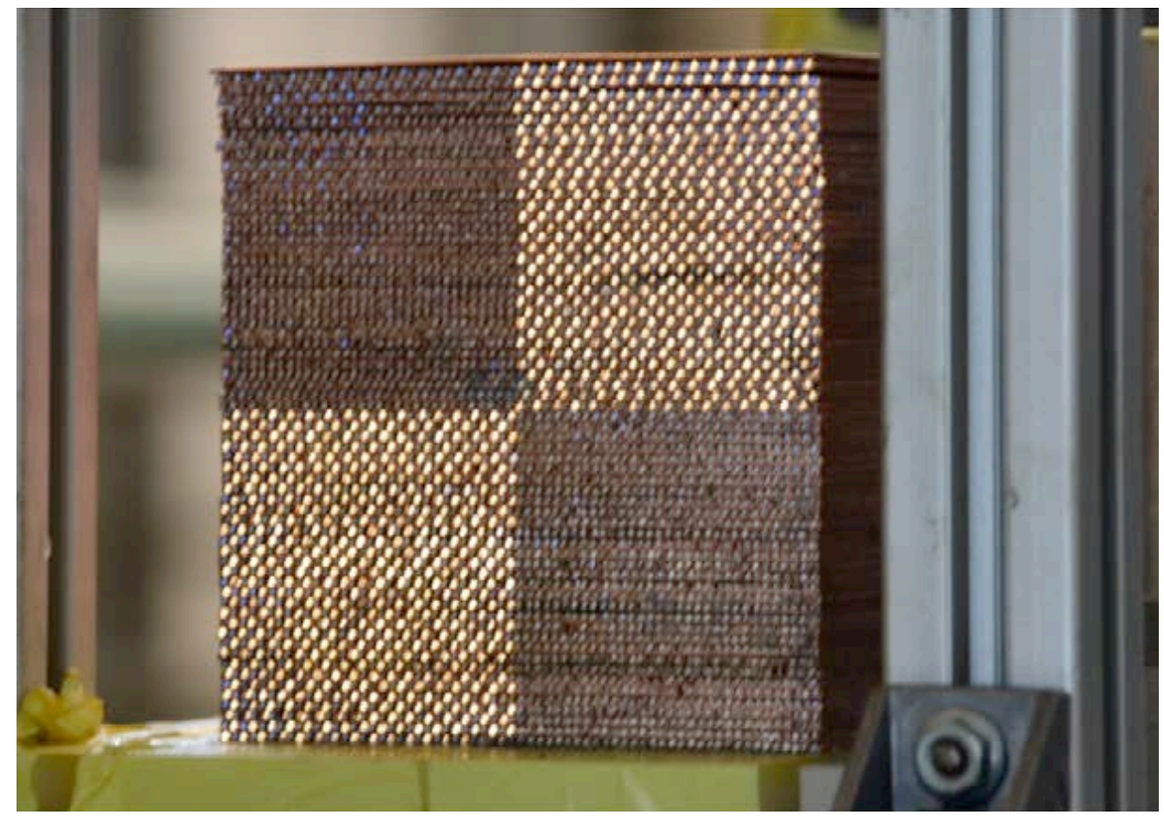


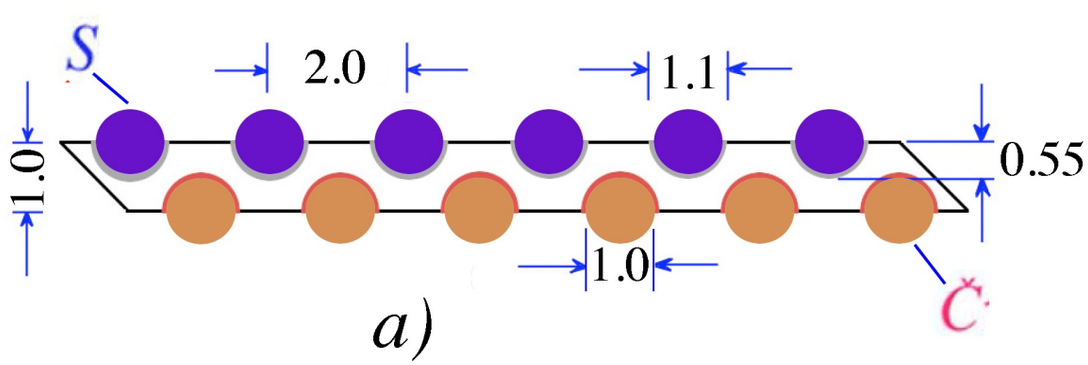
The structures of Pb and Cu modules

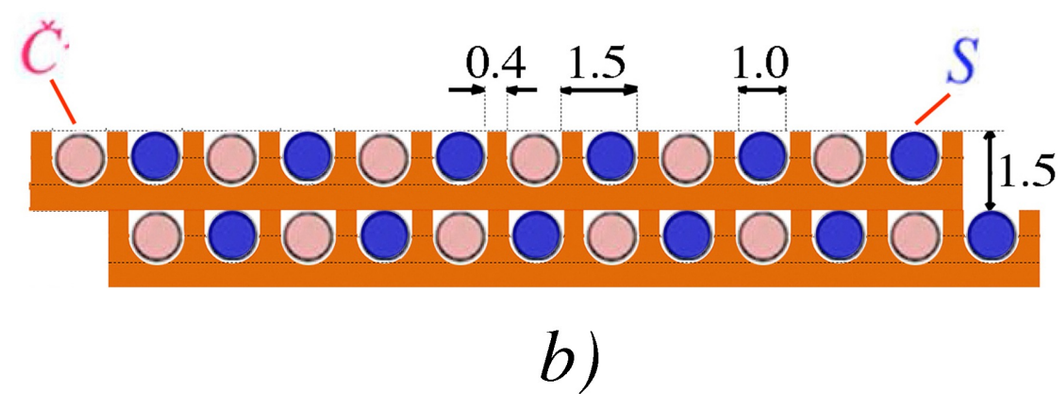
Pb



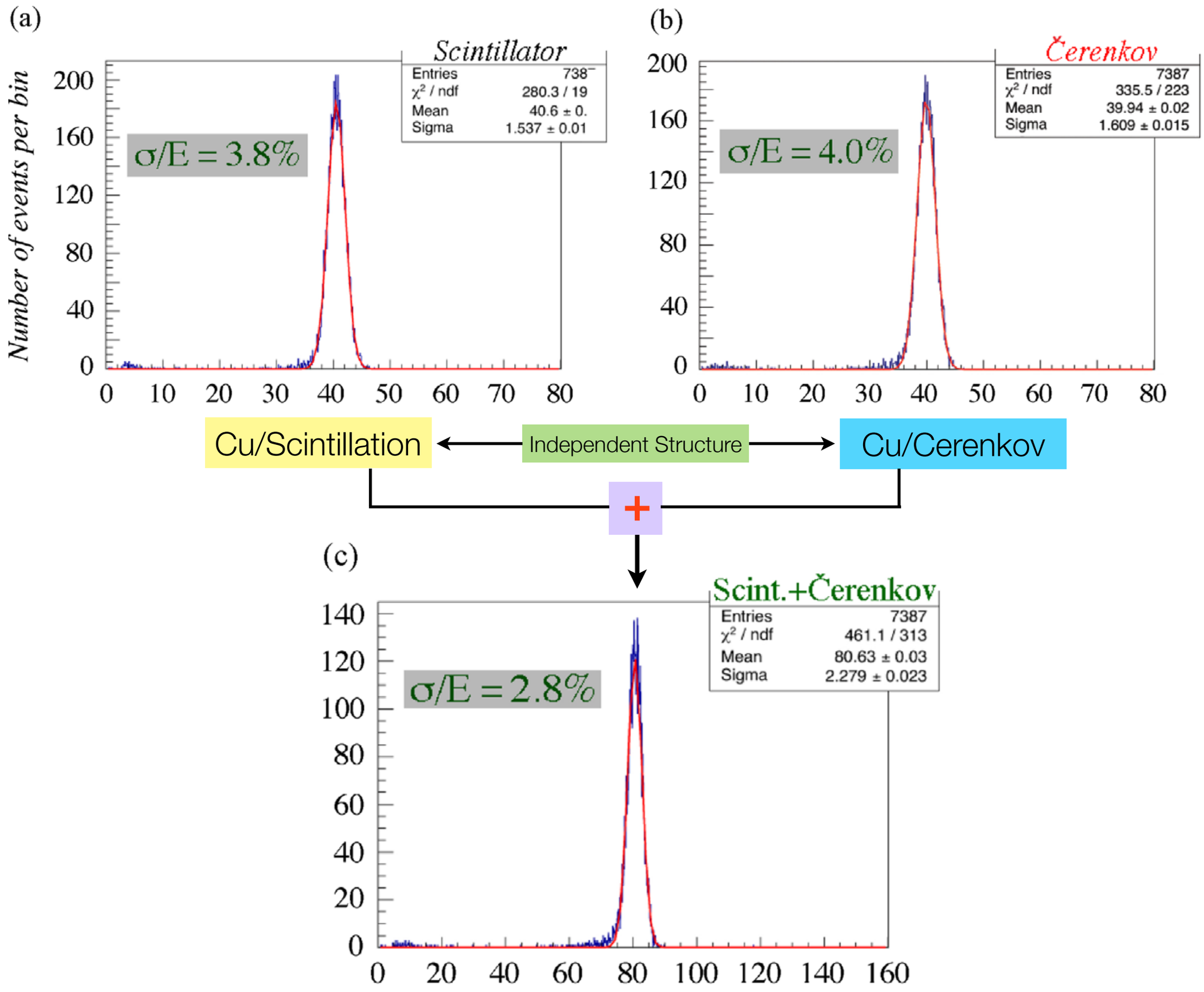
Cu







The electromagnetic performance for 40 GeV e^- (Cu/fiber)

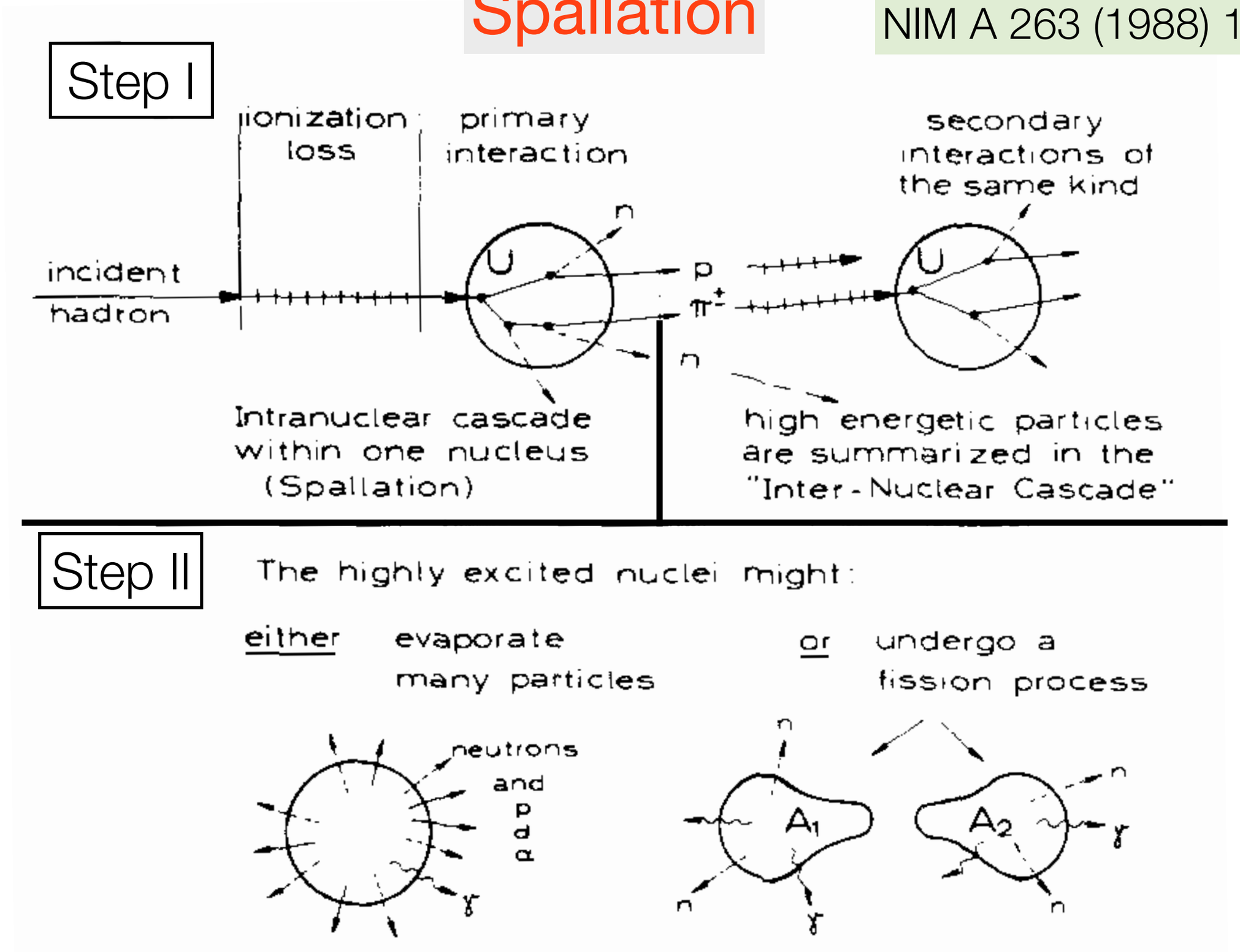


Hadron Shower

Hadron Shower

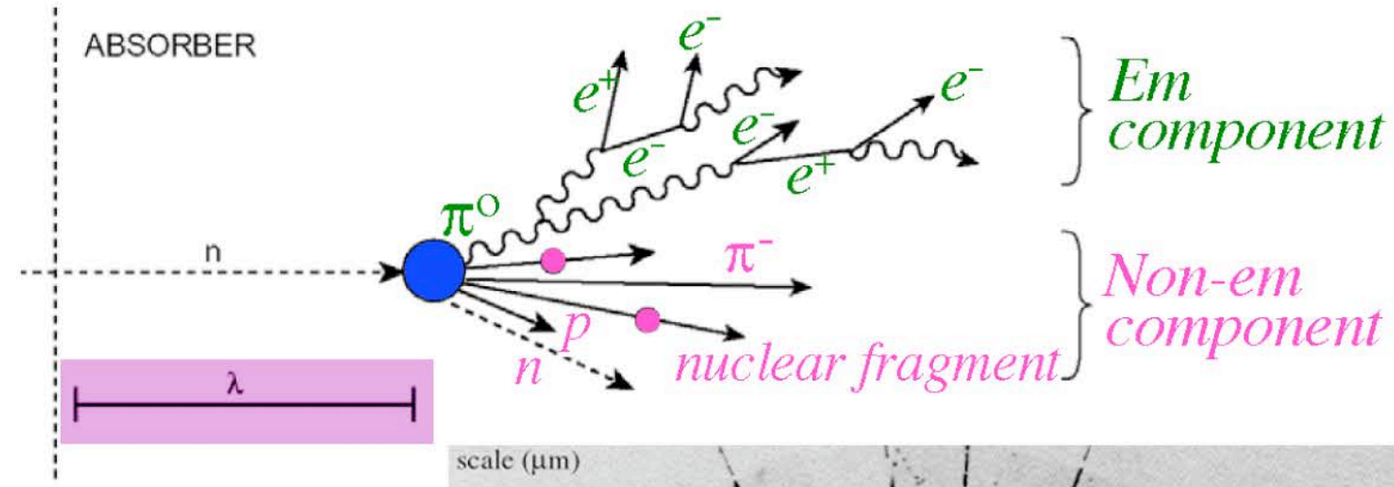
Spallation

NIM A 263 (1988) 136

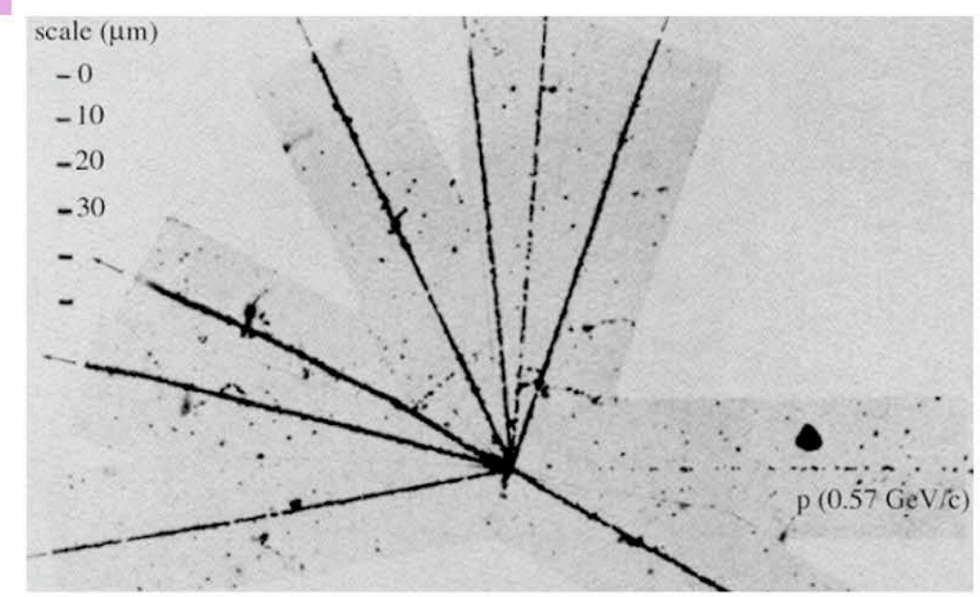


Hadron Shower

- *A hadronic shower consists of two components*



- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)

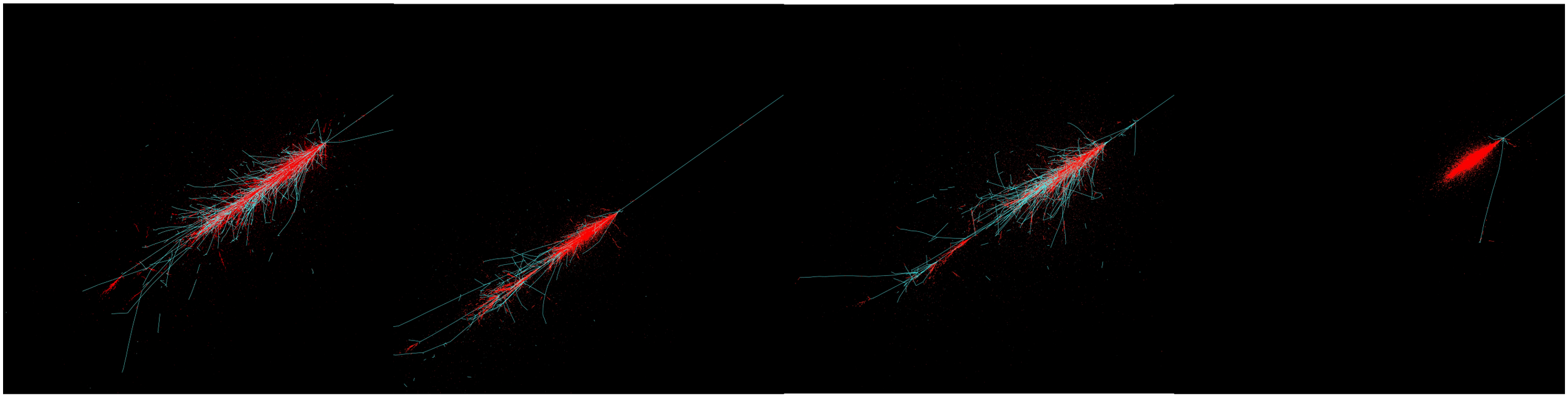


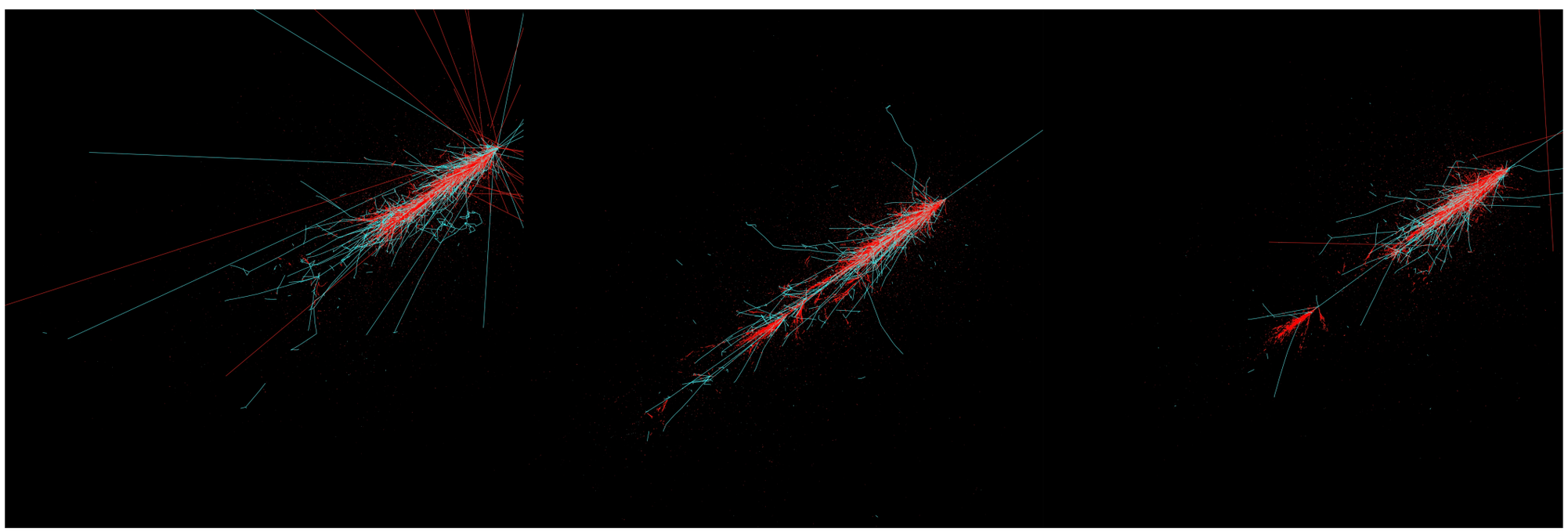
- Main fluctuations in hadron calorimetry:
  - Large, non-Gaussian **electromagnetic component fluctuation**
  - Large, non-Gaussian **fluctuation in nuclear binding energy loss** ("invisible")

Fluctuations of Hadron Showers

500 GeV Pions, Cu absorber

Red: e^-, e^+ ***Cyon: Other Charged Particles***





Particle Sector

- On average, approximately **one-third (1/3) of the mesons** produced in **the first interactions** are **neutral pions**

- In **the second generation of nuclear interaction**, the remaining hadrons may also produce **neutral pions** if they are **sufficiently energetic**.

- Since the production of neutral pions by strongly interacting mesons is an irreversible process, **the average fraction of the initial hadron energy converted into neutral pions gradually increase with energy**.

$$f_{\mathrm{em}} = 1 - \left(\frac{E}{E_0}\right)^{(k-1)}$$

- E_0: the average energy needed for the production of one pion

- E/E_0: the total number of pions (in the absence of an em shower component)

- k: the energy dependence of the em shower fraction. Determined by **the average fraction of neutral pions** production per nuclear interaction and **the average multiplicity** (average number of mesons) per nuclear interaction <m>

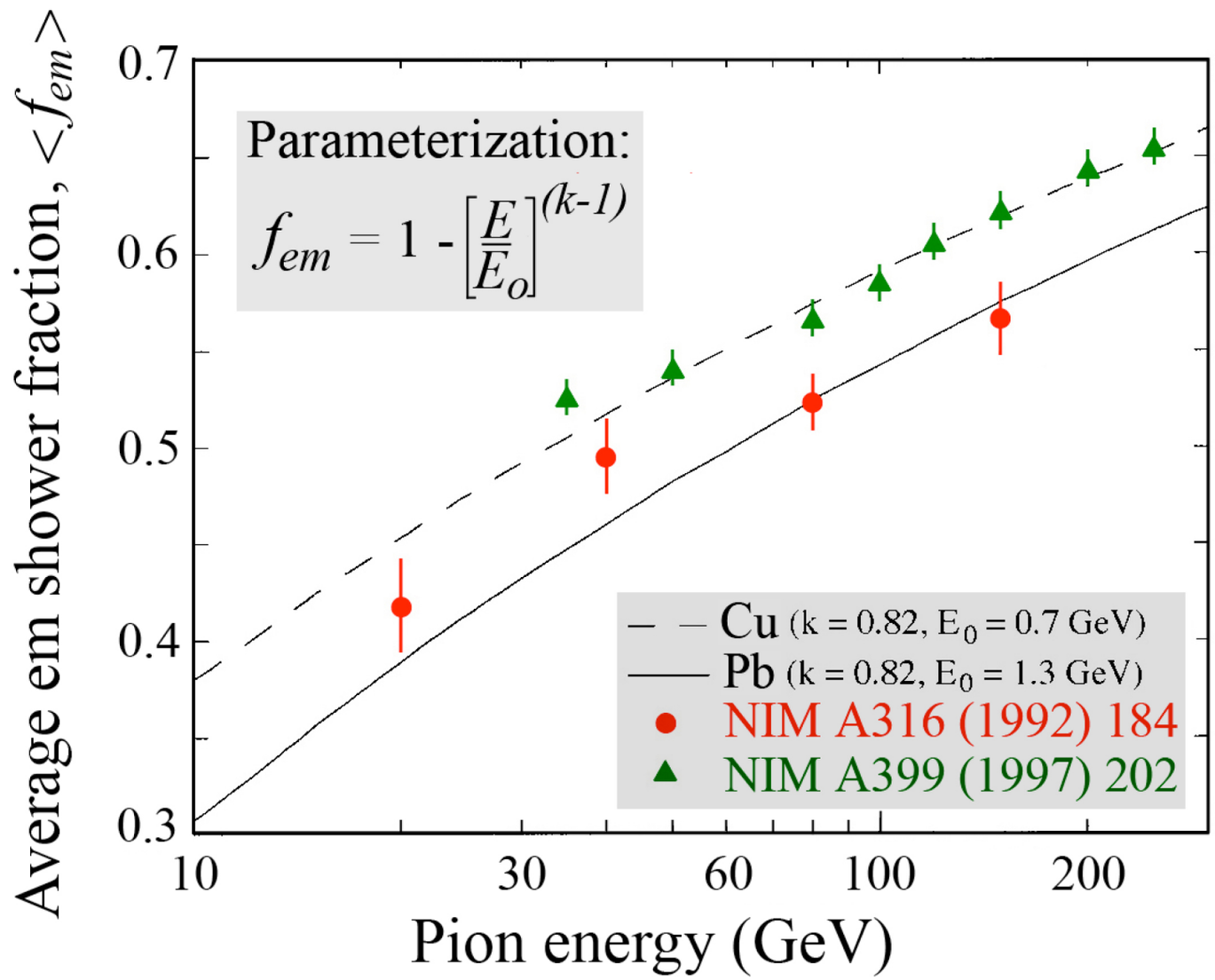


FIG. 2.25. Comparison between the experimental results on the em fraction of pion-induced showers in the (copper-based) QFCAL and (lead-based) SPACAL detectors. Data from [Akc 97] and [Aco 92b].

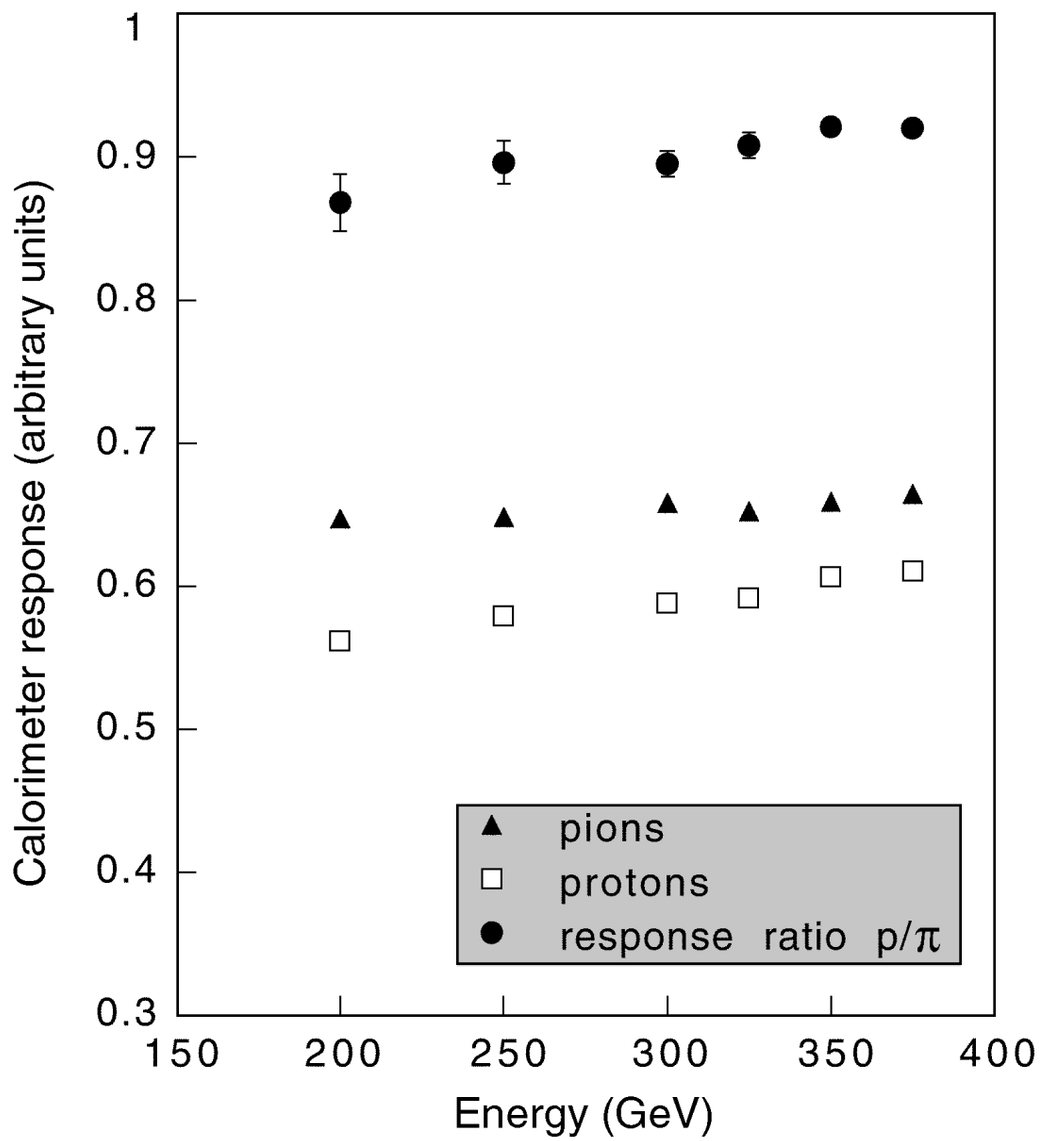


FIG. 2.26. The calorimeter response to protons and π^- mesons, and the ratio of these responses, as a function of energy, measured with the QFCAL detector. Data from [Akc 98].

Calorimeter response: the average calorimeter signal per GeV

The response to proton is systematically **smaller** than **the response to pions** of the same energy: ~13% at 200 GeV, ~8% at 375 GeV

Nuclear Sector

- Nuclear spallation reaction
  - Spallation is described as a two-stage process:
    - a fast intra-nuclear cascade
    - followed by a slower evaporation stage

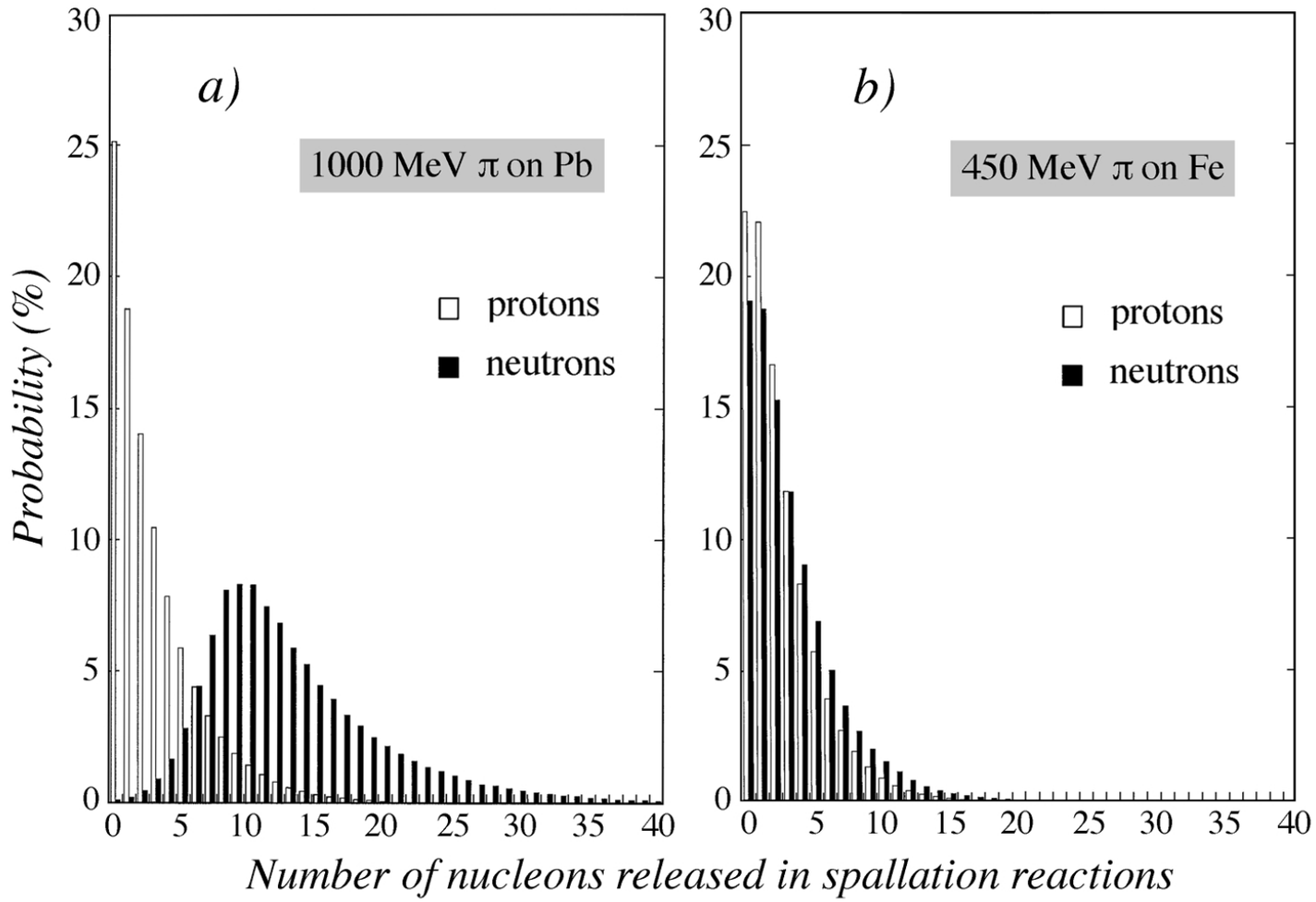


FIG. 2.30. Distribution of the numbers of protons and neutrons produced in spallation reactions induced by 1000 MeV pions on $^{208}_{82}$Pb (a) and by 450 MeV pions on $^{56}_{26}$Fe (b).

- **Spallation nucleons**
  - Final state nucleus: (A_f,Z_f)
  - In **lead** absorber: **(208-A_f) nucleons**, and **(82-Z_f) protons** are released
  - In the above figure, on average, 2.7 protons, 12.8 neutrons are produced in the spallation reactions (a) (large discrepancy in # of protons and neutrons)

- The **cascade nucleons** (particular cascade neutrons) are likely to induce **new spallation reactions**, further **increasing the numbers of evaporation neutrons**

- The **cascade particles** have a **momentum component** along **the direction of the incoming particle**

- Therefore, the residual target nucleus undergoes a net recoil

- This **recoil energy** is, in general, **not measurable**. This energy has to be considered part of the **invisible component of the shower energy**

- The evaporation neutrons are emitted isotropically

- **Evaporation neutrons**

  - Neutrons depend entirely on the **strong interaction** (sometimes the weak).

  - The **kinetic energy spectrum of the evaporation neutrons** is described by **Boltzmann-Maxwell distribution** with the temperature of about 2 MeV

$$\frac{dN}{dE} = \sqrt{E}\exp(-E/T)$$

  - **the average kinetic energy** of these neutrons amounts to about **3 MeV**

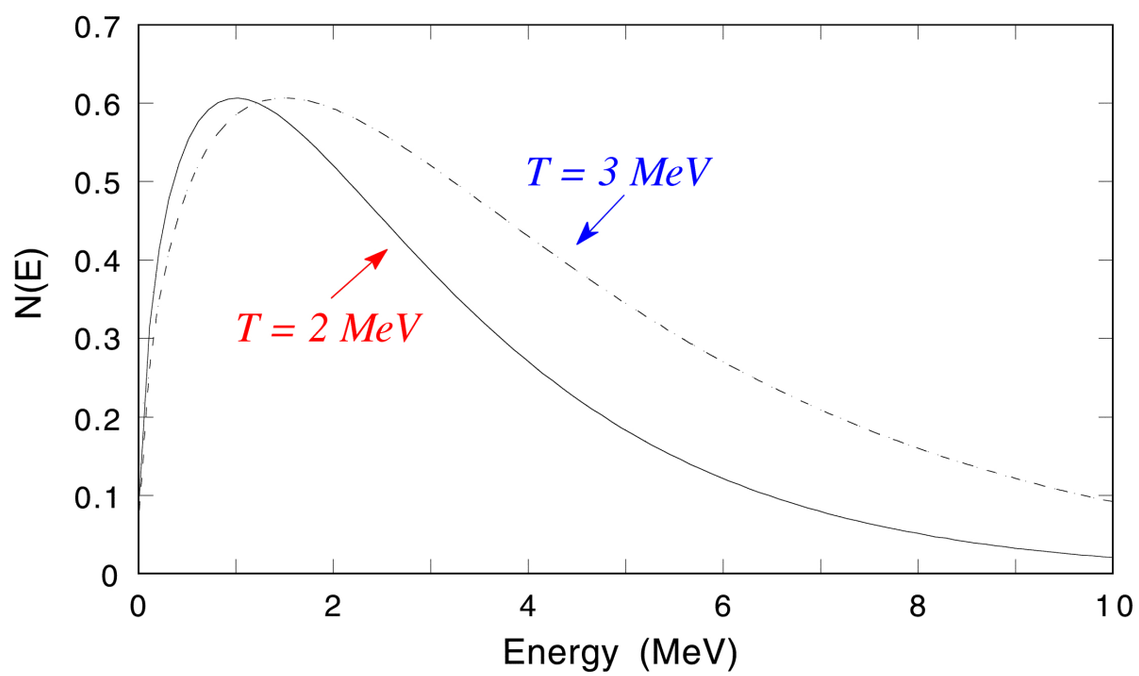


FIG. 2.32. Kinetic energy spectrum of evaporation neutrons, produced according to a Maxwell distribution with a temperature of 2 MeV. For comparison, the spectrum for a temperature of 3 MeV is given as well.

The interactions of neutrons with matter

- **Elastic neutron scattering**
  - energies between **a few eV and approximately 1 MeV**: elastic scattering is by far the dominant
  - f (the energy fraction) lost by neutrons in collisions with nuclei (A, atomic number): 0 (glancing collisions) ~ $4A/(A+1)^2$ (central collisions)
  - f (average): 50% (hydrogen), 3.4% (iron), 0.96% (lead)
  - **energy loss** by the elastic scattering is **most efficient for hydrogen**
  - **hydrogen-rich compounds**: the material of choice for **neutron shielding** purpose in nuclear reactor

- **Neutron capture**
  - When the neutrons have **lost (almost) all of their kinetic energy** in collisions with the target material:
    - **decay** (mean lifetime ~15 min) or **captured by an atomic nucleus**
  - **Capture** is much more likely to occur
  - When a neutron is capture by an atomic nucleus, the **nuclear binding energy** is **gained back**
  - The excited compound nucleus gets rids of this excess energy by **emitting gamma-rays**.
  - **Li and B**, the capture of a neutron may be followed by the emission of an **alpha particle**
  - **Charged particles**: become **part of the absorbing structure** after losing their kinetic energy through ionization of the calorimeter material
  - The **neutrons** transforms an absorber into **another type of nucleus**

- **Inelastic neutron scattering**
  - **Part of the neutron's kinetic energy** is used to bring a **nucleus** in an **excited state**.
  - The excited nucleus releases **the excitation energy** in the form of **one or several gamma's**
  - The contribution of this process to the energy loss of the neutron depends on details of the **nuclear level structure**
    - For **lead**, it becomes **insignificant below 2.6 MeV** (energy to bring the lead nucleus from its ground state into the lowest excited state)
    - For **iron (^{56}Fe)**, **the first excited state** is located **0.85 MeV** above the ground state
- **Neutrons** in the energy range of **1-6 MeV** lose 0.85 MeV. Steel-reinforced concrete is a good shielding material for MeV-type neutrons.

Hadronic shower profile

- **The nuclear interaction length**
  - **the nuclear interaction length (λ_{int})**: the average distance a high-energy hadron had to travel inside that medium before a nuclear interaction occurs.
  - The **probability** that the particle traverses a **distance z** in this medium ***without*** causing **a nuclear interaction**: **P= exp ($-z/\lambda_{int}$)**
  - Total cross section for nuclear interactions: A (atomic weight)

$$\sigma_{\mathrm{tot}} = \frac{A}{N_{\mathrm{A}} \lambda_{\mathrm{int}}}$$

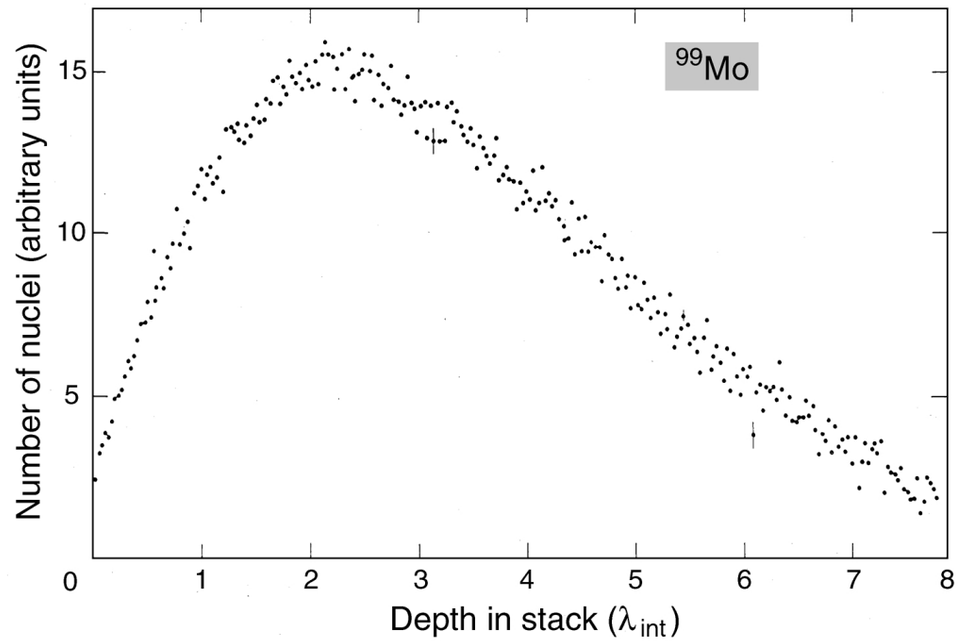


FIG. 2.34. Longitudinal shower profile for 300 GeV π^- interactions in a block of uranium, measured from the induced radioactivity. The ordinate indicates the number of radioactive decays of a particular nuclide, ^{99}Mo, produced in the absorption of the high-energy pions. Data from [Ler 86].

- **Longitudinal shower profiles**
  - initially rises roughly linearly, reaches a maximum, followed by a decay (less steep than the initial rise)
  - stack of 3 mm thick plates of **depleted uranium** (250)
  - **300 GeV negative pions**
  - A very larger number of nuclei produced in reactions by shower particles were unstable
  - The number of radioactive decays of ^{99}Mo (y-axis)
  - on average **8 λ_{int} of U (~85 cm)** to contain **300 GeV π** showers at the **95% level**
  - containment of **300 GeV electrons** at the **95% level**: **10 cm of U**.

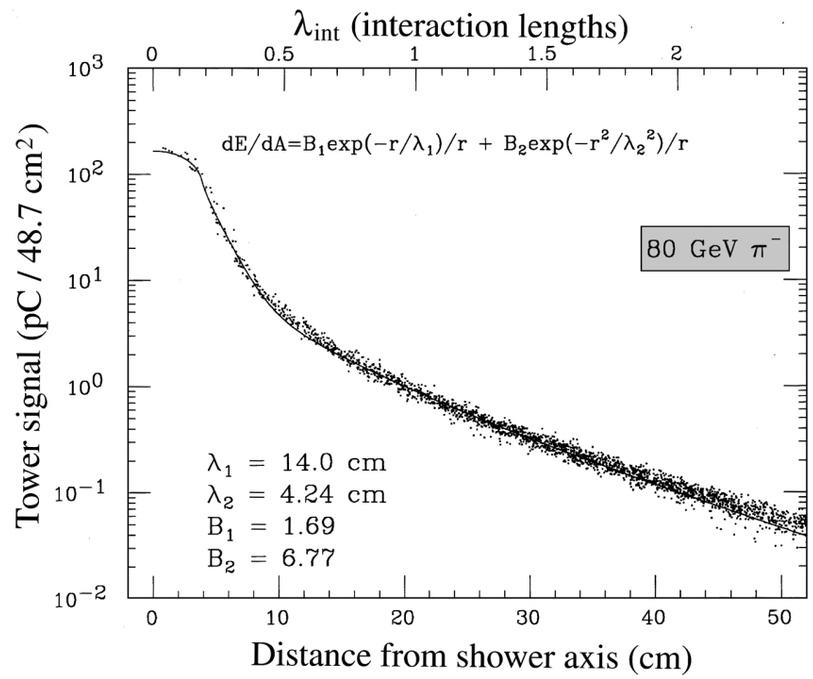


FIG. 2.38. Average lateral profile of the energy deposited by 80 GeV π^-showering in the SPACAL detector. The collected light per unit volume is plotted as a function of the radial distance to the impact point. Data from [Aco 92b].

- **Lateral/radial profiles**
  - Hadron showers: **deeper, broader than em showers**
  - collected light per unit volume as a function of the radial distance
  - The narrow **core**: the **em shower component** caused by π^0
  - The **halo**: exponentially decreasing, caused by the **non-em shower component**
  - the radius of the cylinder to contain 80 GeV π^- at the 95% level: 32 cm (1.5 λ_{int}), 3.5 cm (2.2 ρ_M) radius for containing 80 GeV em shower at the 95% level (9 times larger)

Shower containment

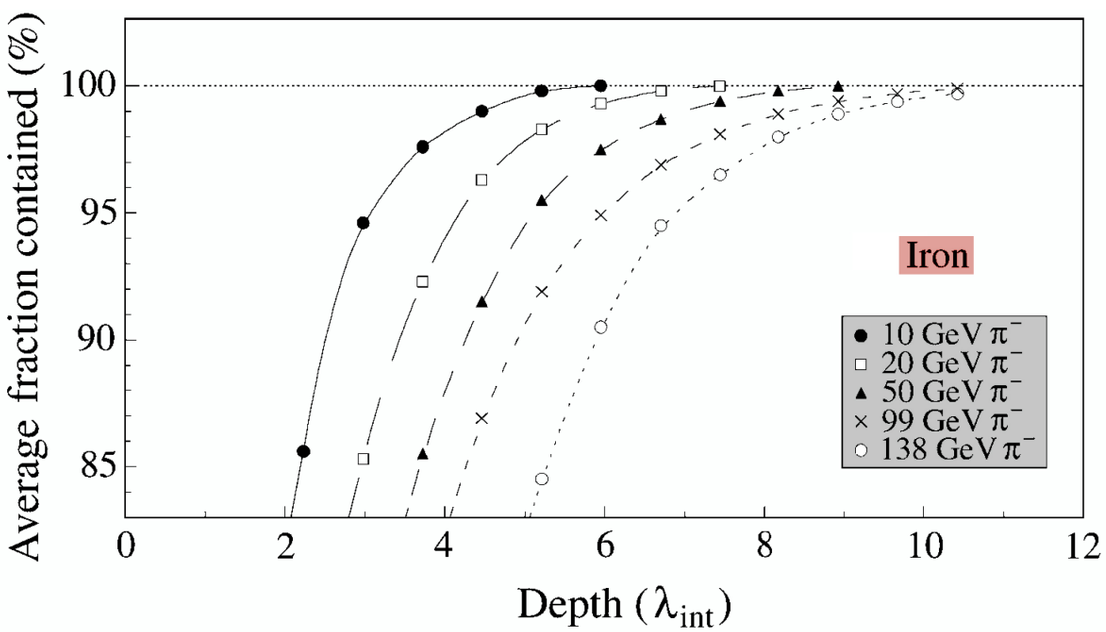


FIG. 2.43. Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of this absorber, expressed in nuclear interaction lengths. Shown are results for showers induced by pions of various energies in iron absorber. Experimental data from [Abr 81].

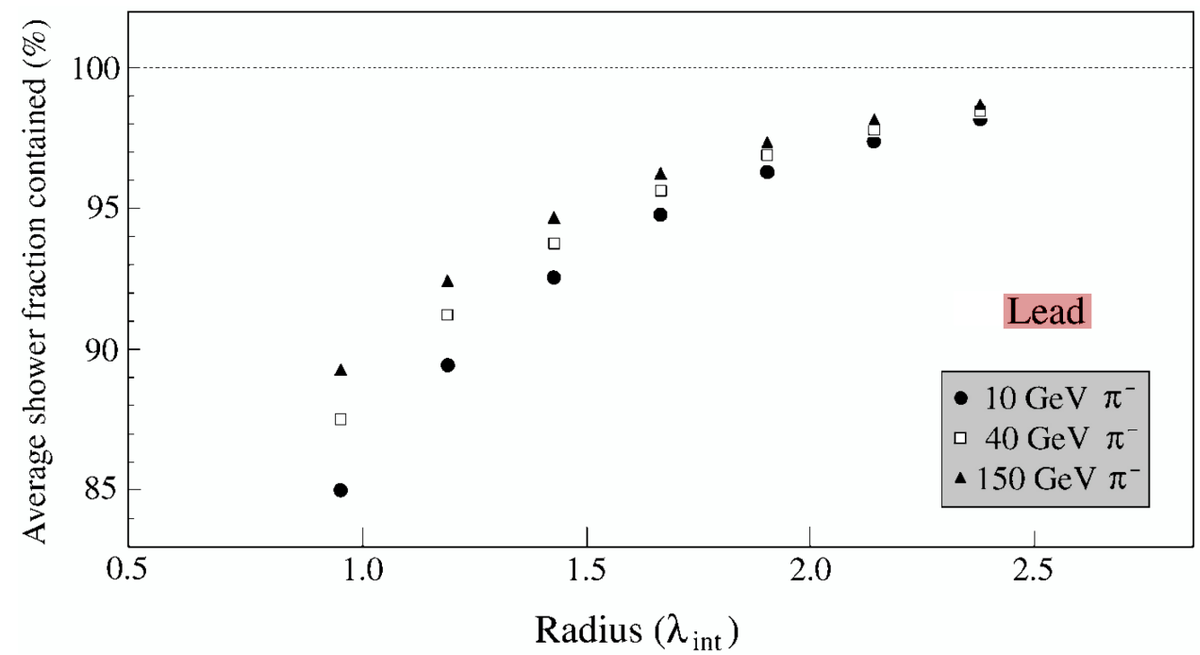


FIG. 2.45. Average energy fraction contained in an infinitely long cylinder of absorber material, as a function of the radius of this cylinder (expressed in nuclear interaction lengths), for pions of different energy showering in lead absorber [Aco 92b].

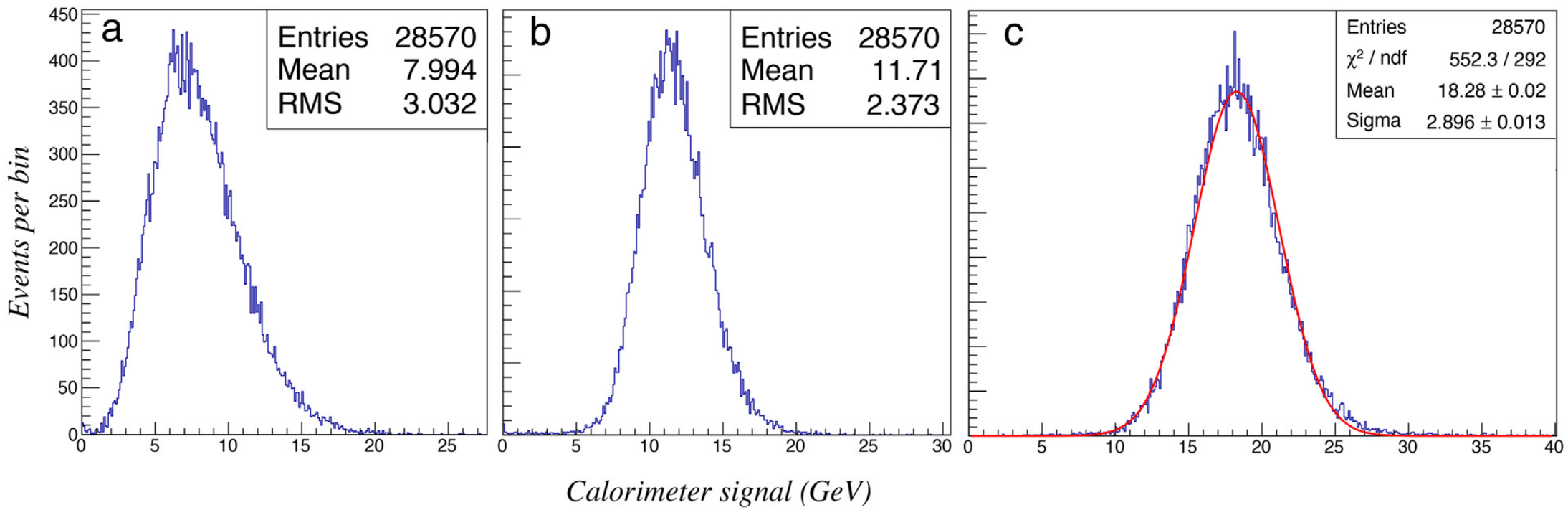


Fig. 11. Signal distributions for 20 GeV π^- particles. Shown are the measured Čerenkov (a) and scintillation (b) signal distributions as well as the signal distribution obtained by combining the two signals according to Eq. (2), using $\chi = 0.45$ (c).

Detection Mechanism

Scintillation

- When **charged particles** traverse matter, they **lose energy** through the **electromagnetic interaction** with the Coulomb fields of the electrons
  - **ionize** the atoms or molecules
  - bring these atoms/molecules into an **excited state** → quickly returns to the ground state
- the **excitation energy** is released in the form of one or more **photons**
- **fluorescence** or **scintillation**: the emitted photons are in the visible domain

Scintillation

- typical time scale range: **10^{-12} ~ 10^{-6} sec**
  - More **complex molecules** → the **shorter time scales** (the density of excited states)
  - Relatively **simple scintillating crystals** (NaI(Tl), BGO): decay times of **several hundred ns**
- Scintillator-based particle detectors:
  - The **photomultiplier tube**: the conversion of single photons into electric signals, noise-free signal amplification, the sensitivity to external magnetic field
  - **Wavelength shifter**: absorb the scintillation light and reemit it at a lower energy (longer wavelength)

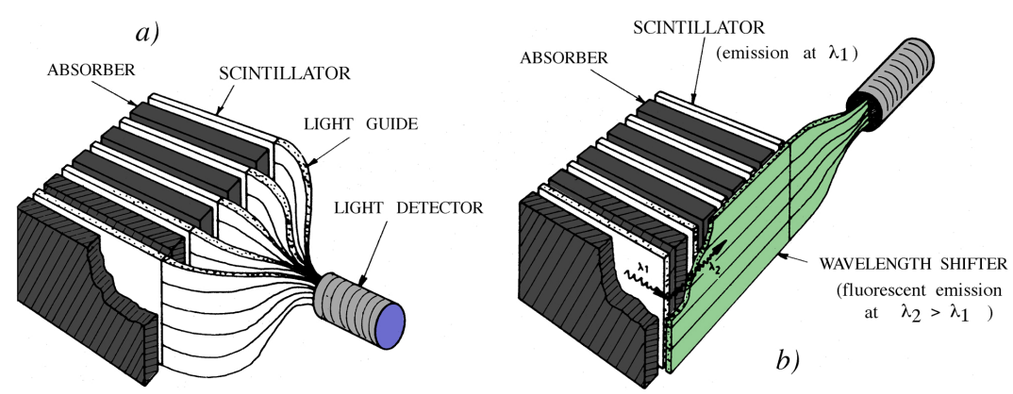


FIG. 1.9. Schematic of the readout systems of scintillator calorimeters without (*a*) and with (*b*) wavelength-shifting plates.

Cerenkov radiation

- **$v > c/n$**
- **$\theta_c = \arccos (n\beta)^{-1}$** (a cone with half-opening angle)
- lose energy by emitting Cerenkov radiation
- the spectrum of Cerenkov radiation: **$1/\lambda^2$**
- very minor source of contributing to the energy loss
- in water, a charged particle with $\beta \simeq 1$ loses ~400 eV per cm in the form of visible Cerenkov photons
- **sensitive to the velocity of particles** → determine the mass of particles of which the momentum has been determined, separation of electrons, kaons, pions, protons, deutrons

Cerenkov radiation

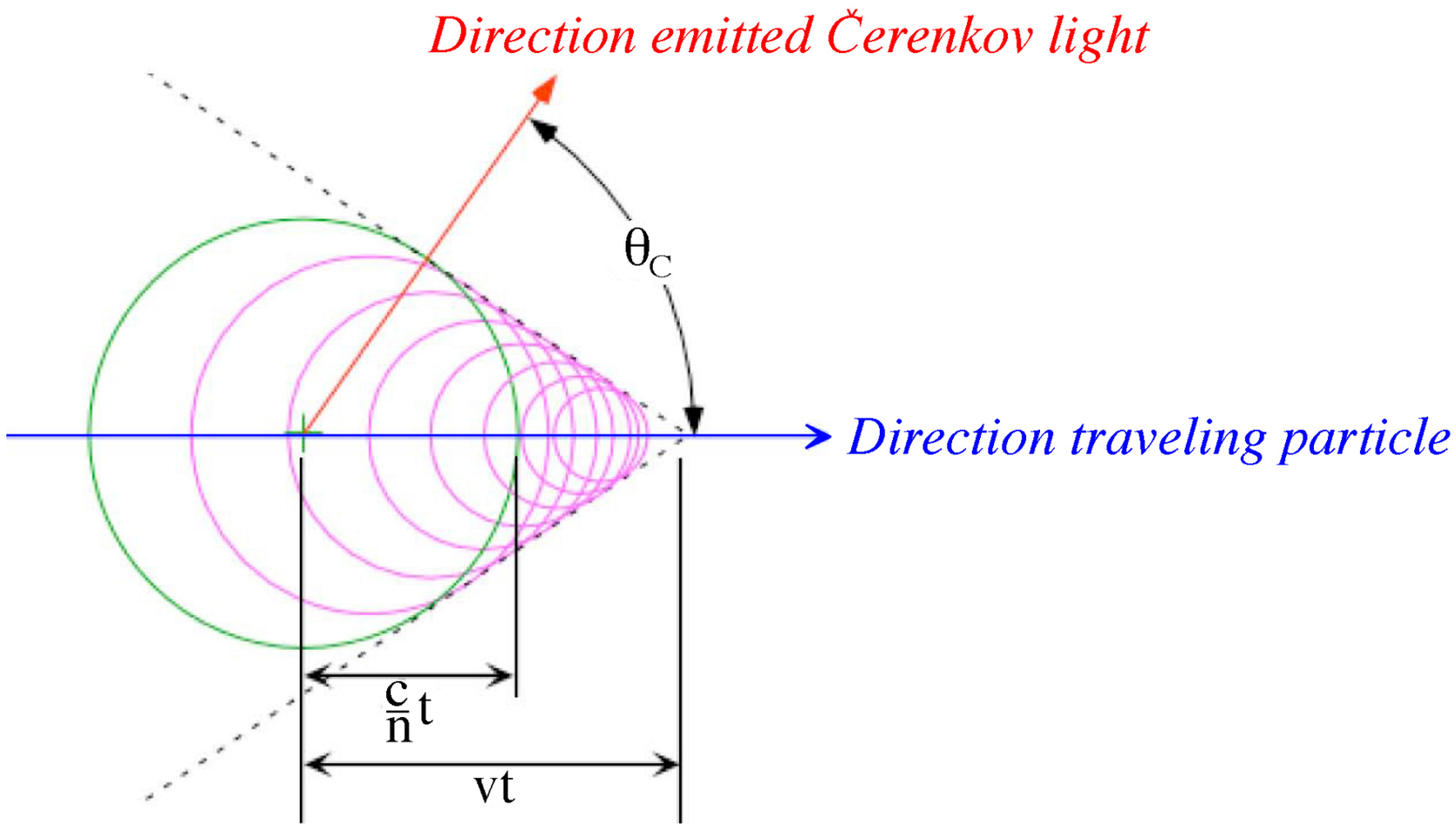


FIG. 1.10. The principle of Čerenkov light emission by a superluminal particle. In a time t, the particle travels a distance vt, while the light it emits travels a distance ct/n. The wavefronts of the light emitted by such a particle form a cone with half-opening angle θ_C.

Ionization

- When charged particles traverse matter, they may ionize the atoms of which this matter consists. One or several electrons are released from their Coulomb field in this process, leaving behind an ionized atom
- Collection of these liberated electrons is applied as the signal producing technique in a wide variety of particle detectors
- noble liquid, gaseous detector, solid state devices