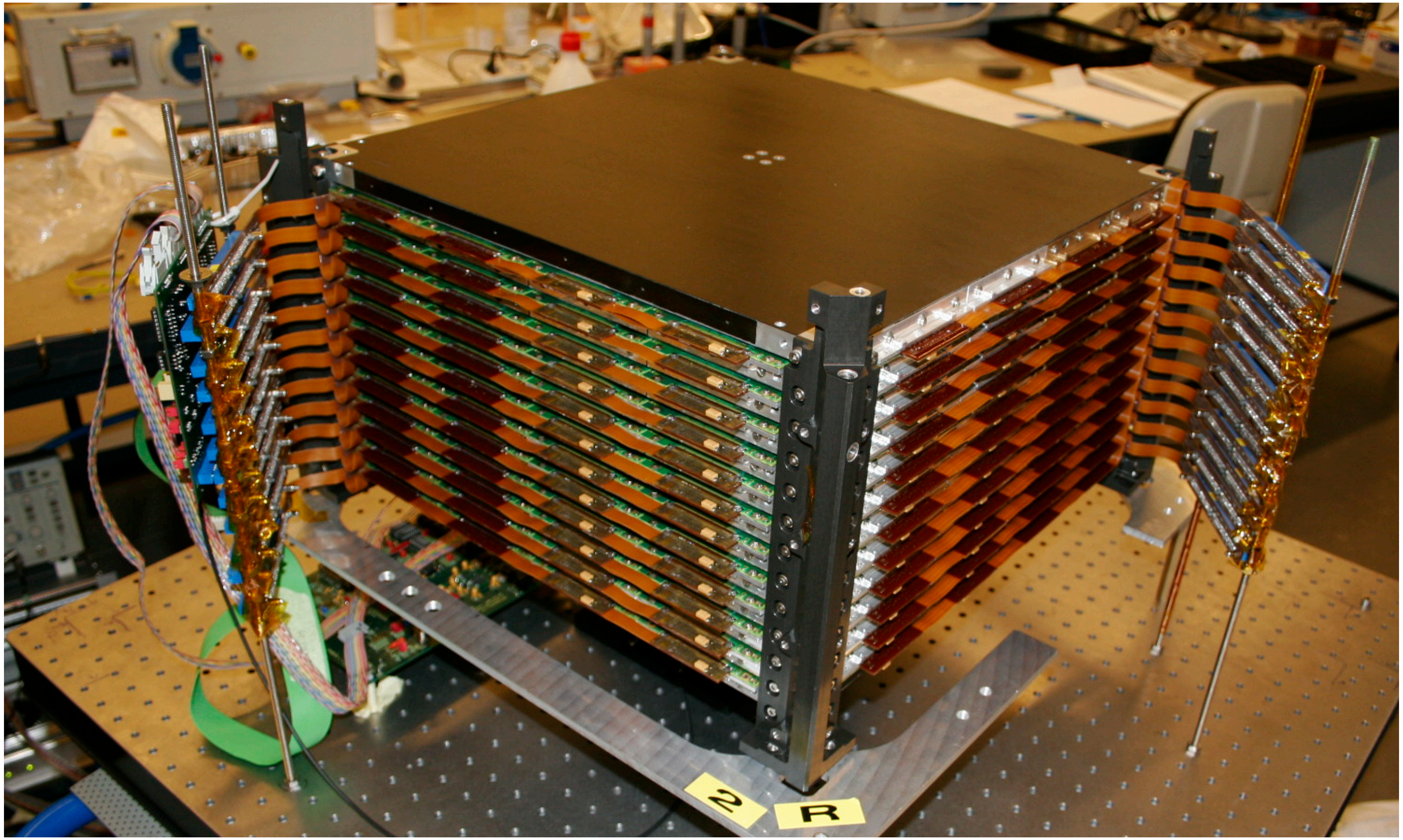
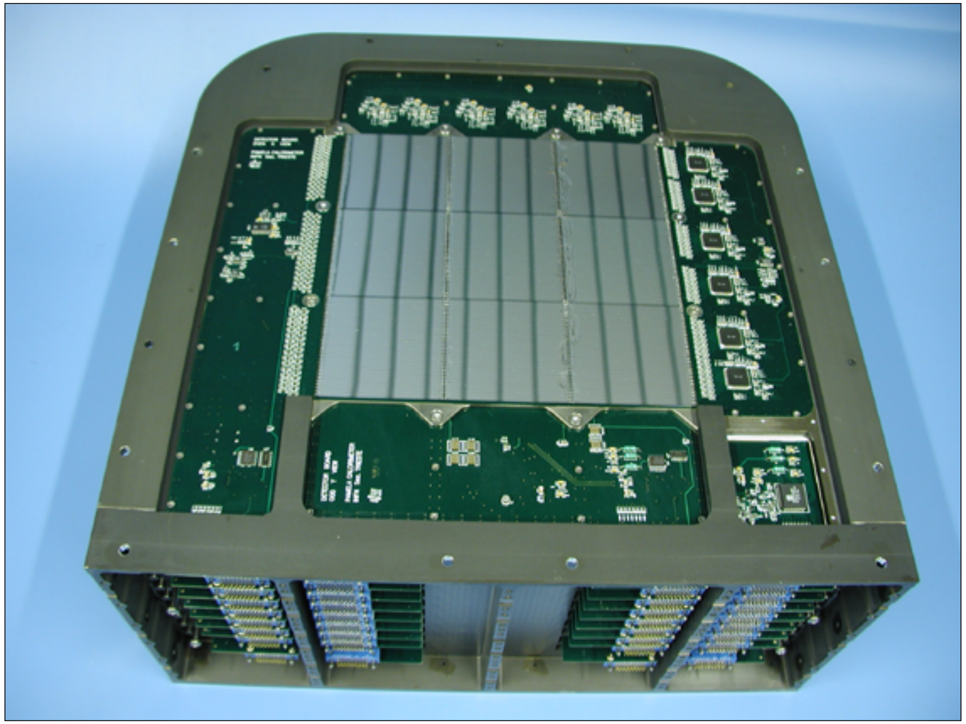
Astrofisica Nucleare e Subnucleare

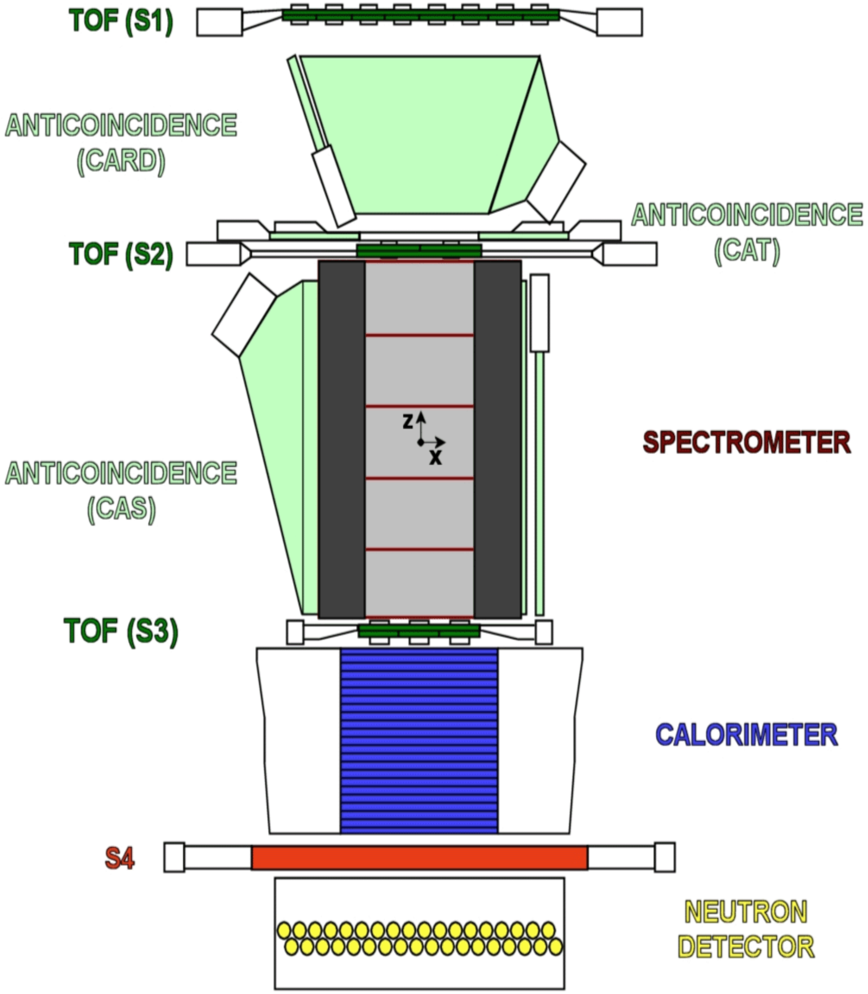
Interazione Radiazione Materia

AGILE

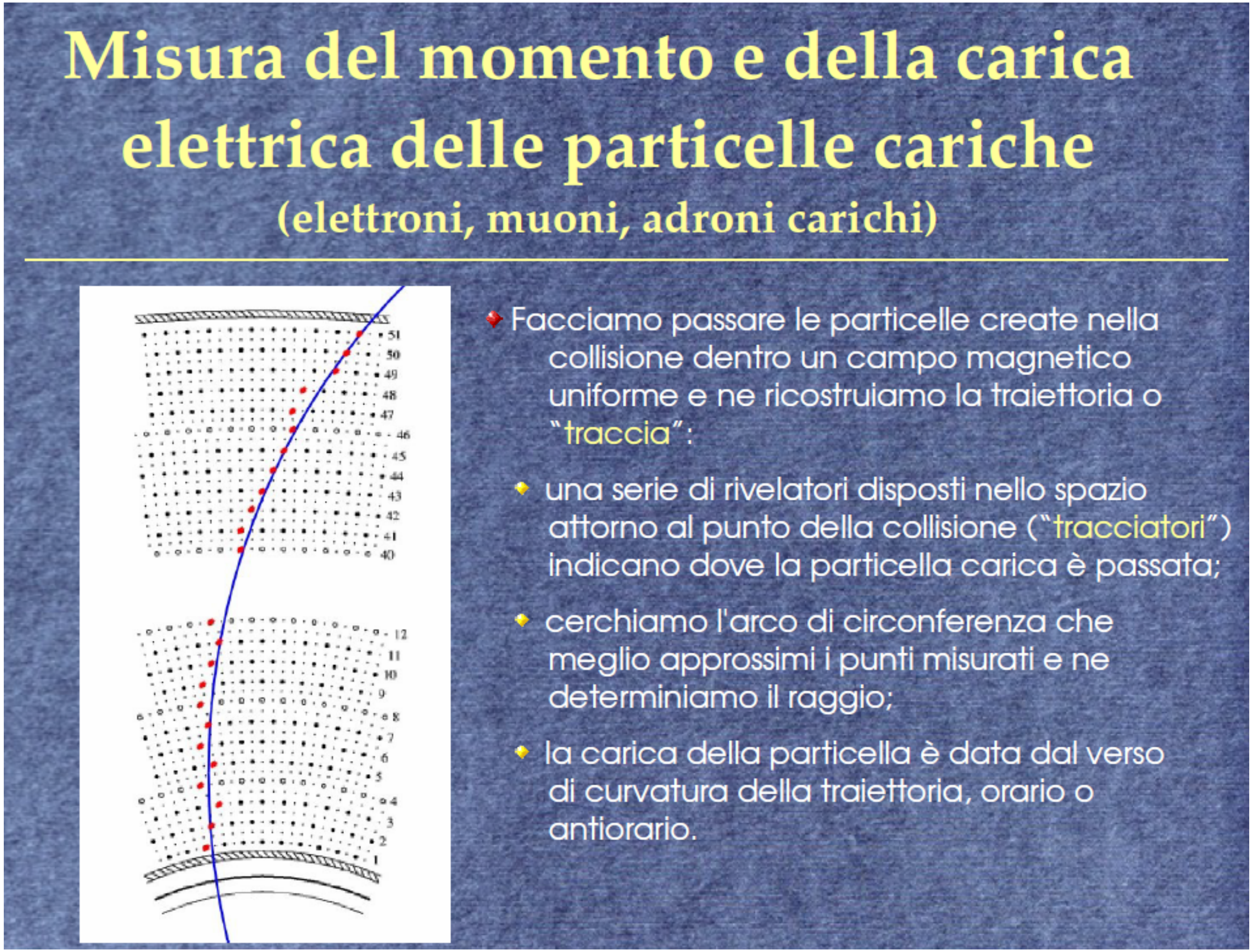


PAMELA




TOF (S1)
ANTICOINCIDENCE (CARD)
ANTICOINCIDENCE (CAT)
TOF (S2)
SPECTROMETER
z
x
ANTICOINCIDENCE (CAS)
TOF (S3)
CALORIMETER
S4
NEUTRON DETECTOR

Rivelazione delle particelle elementari

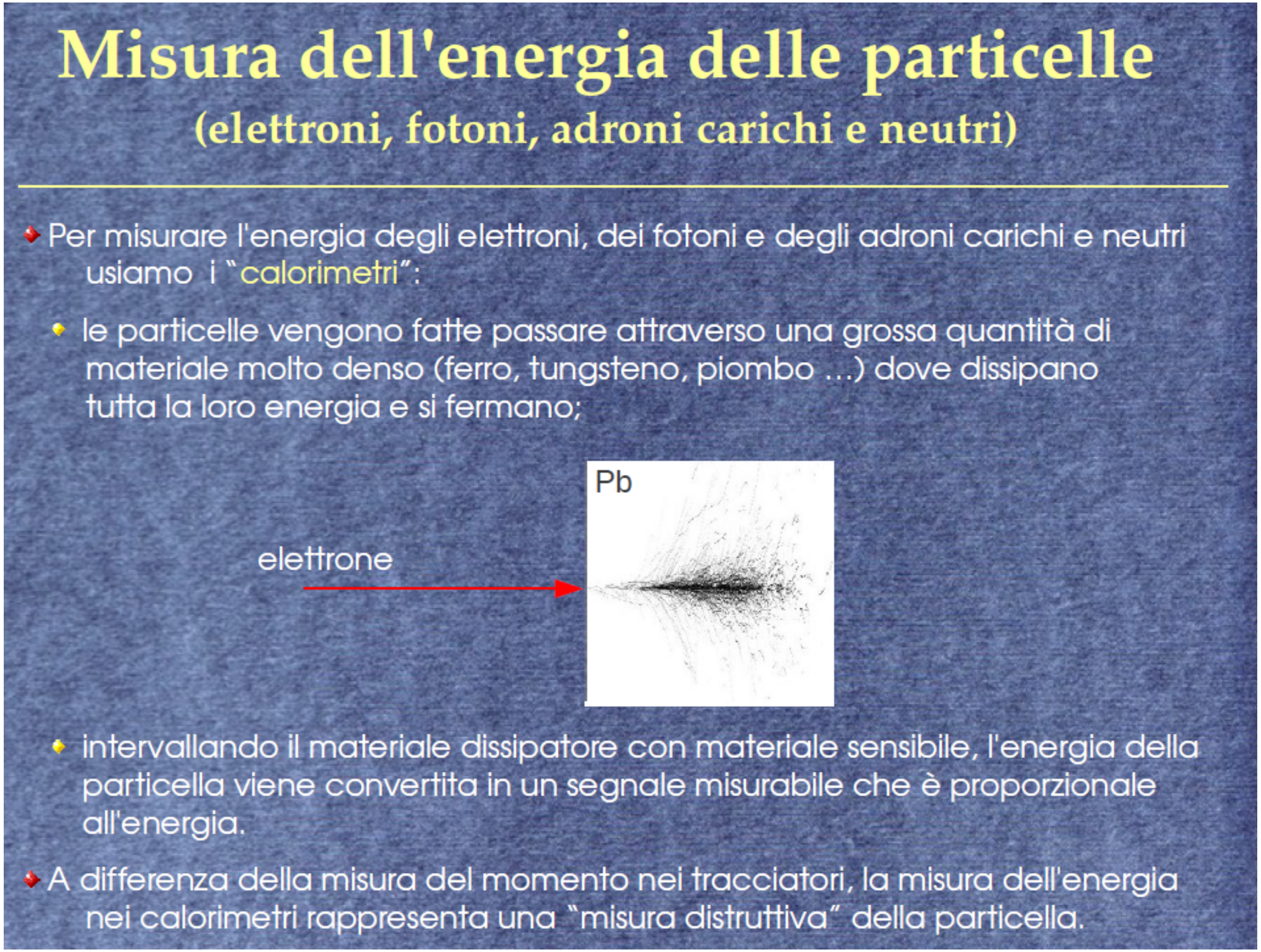


Misura del momento e della carica elettrica delle particelle cariche

(elettroni, muoni, adroni carichi)

- Facciamo passare le particelle create nella collisione dentro un campo magnetico uniforme e ne ricostruiamo la traiettoria o "traccia":
  - una serie di rivelatori disposti nello spazio attorno al punto della collisione ("tracciatori") indicano dove la particella carica è passata;
  - cerchiamo l'arco di circonferenza che meglio approssimi i punti misurati e ne determiniamo il raggio;
  - la carica della particella è data dal verso di curvatura della traiettoria, orario o antiorario.

Rivelazione delle particelle elementari



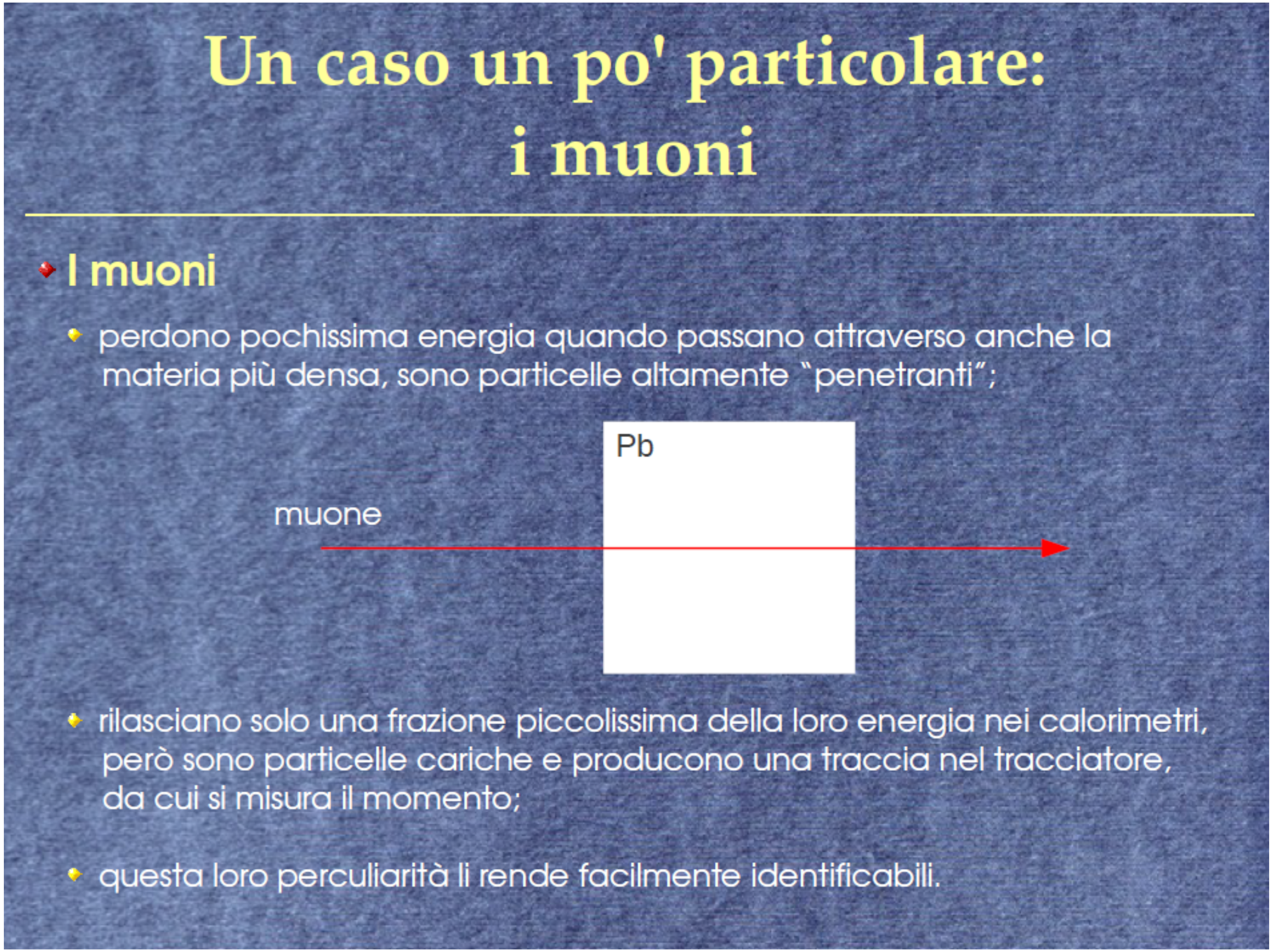
Misura dell'energia delle particelle

(elettroni, fotoni, adroni carichi e neutri)

- Per misurare l'energia degli elettroni, dei fotoni e degli adroni carichi e neutri usiamo i "calorimetri":
  - le particelle vengono fatte passare attraverso una grossa quantità di materiale molto denso (ferro, tungsteno, piombo ...) dove dissipano tutta la loro energia e si fermano;

  - intervallando il materiale dissipatore con materiale sensibile, l'energia della particella viene convertita in un segnale misurabile che è proporzionale all'energia.
- A differenza della misura del momento nei tracciatori, la misura dell'energia nei calorimetri rappresenta una "misura distruttiva" della particella.

Rivelazione delle particelle elementari



Un caso un po' particolare: i muoni

- **I muoni**
  - perdono pochissima energia quando passano attraverso anche la materia più densa, sono particelle altamente "penetranti";

  - rilasciano solo una frazione piccolissima della loro energia nei calorimetri, però sono particelle cariche e producono una traccia nel tracciatore, da cui si misura il momento;
  - questa loro perculiarità li rende facilmente identificabili.

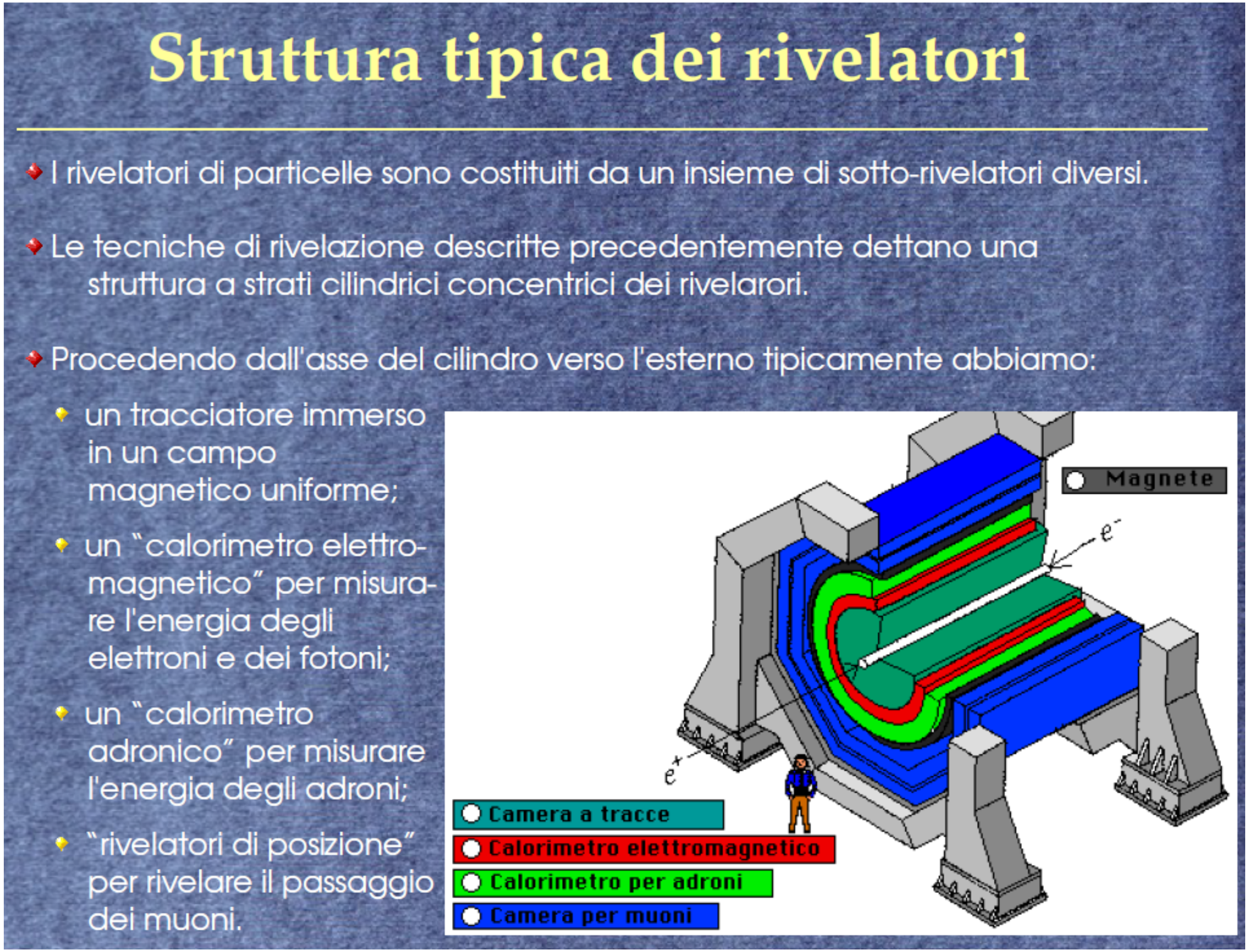
Rivelazione delle particelle elementari

Un caso ancora più particolare: i neutrini

- **I neutrini**
  - sono particelle neutre, che interagiscono pochissimo con la materia che attraversano;
  - non vengono rivelati direttamente: non lasciano tracce nel tracciartore né energia nei calorimetri;
  - la loro presenza è però indicata indirettamente dal momento ed energia mancanti:

    momento ed energia totali si conservano tra prima e dopo la collisione, una mancanza di momento o energia indicano la presenza di particelle non rivelate.

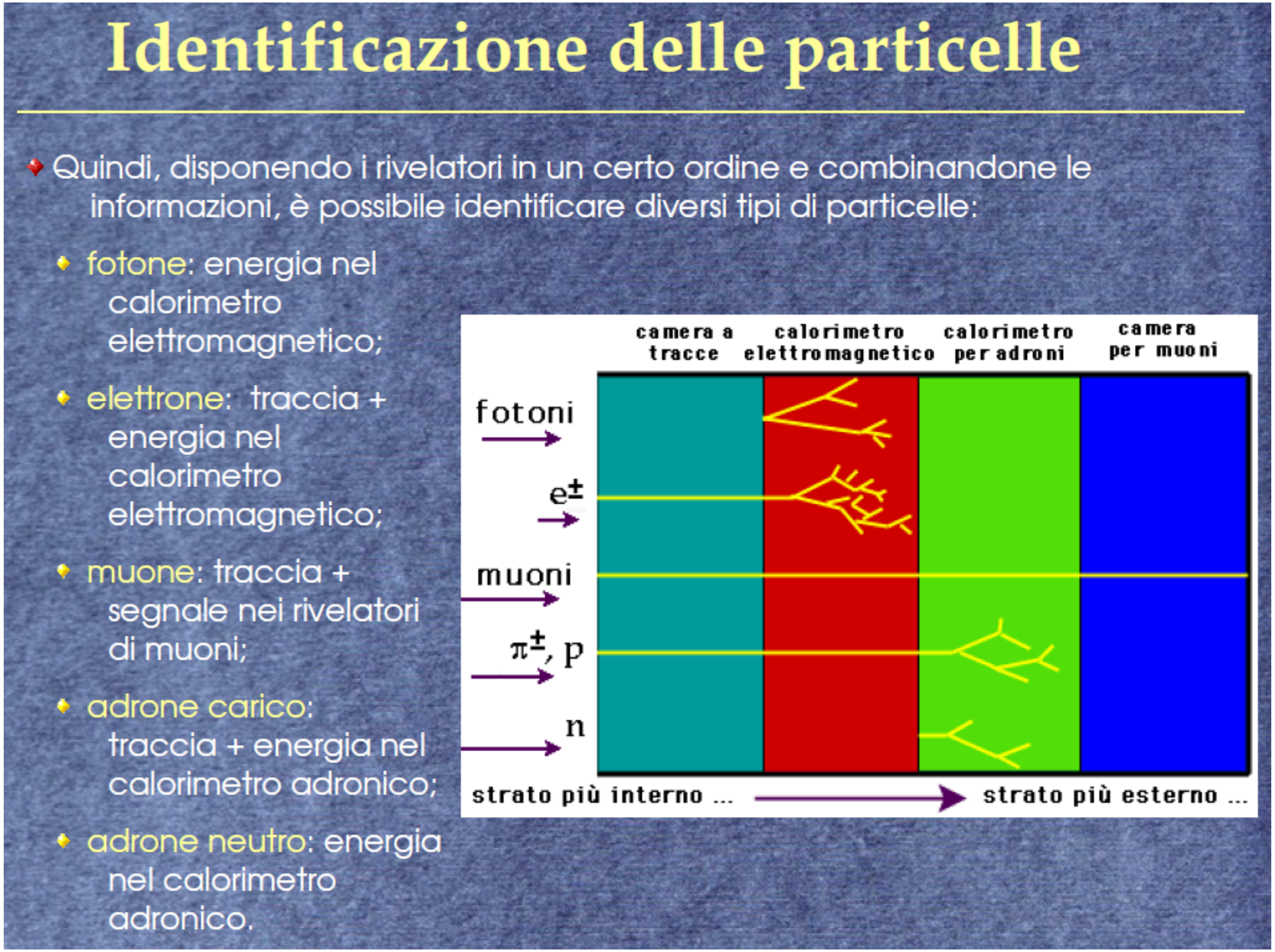
Rivelazione delle particelle elementari



Struttura tipica dei rivelatori

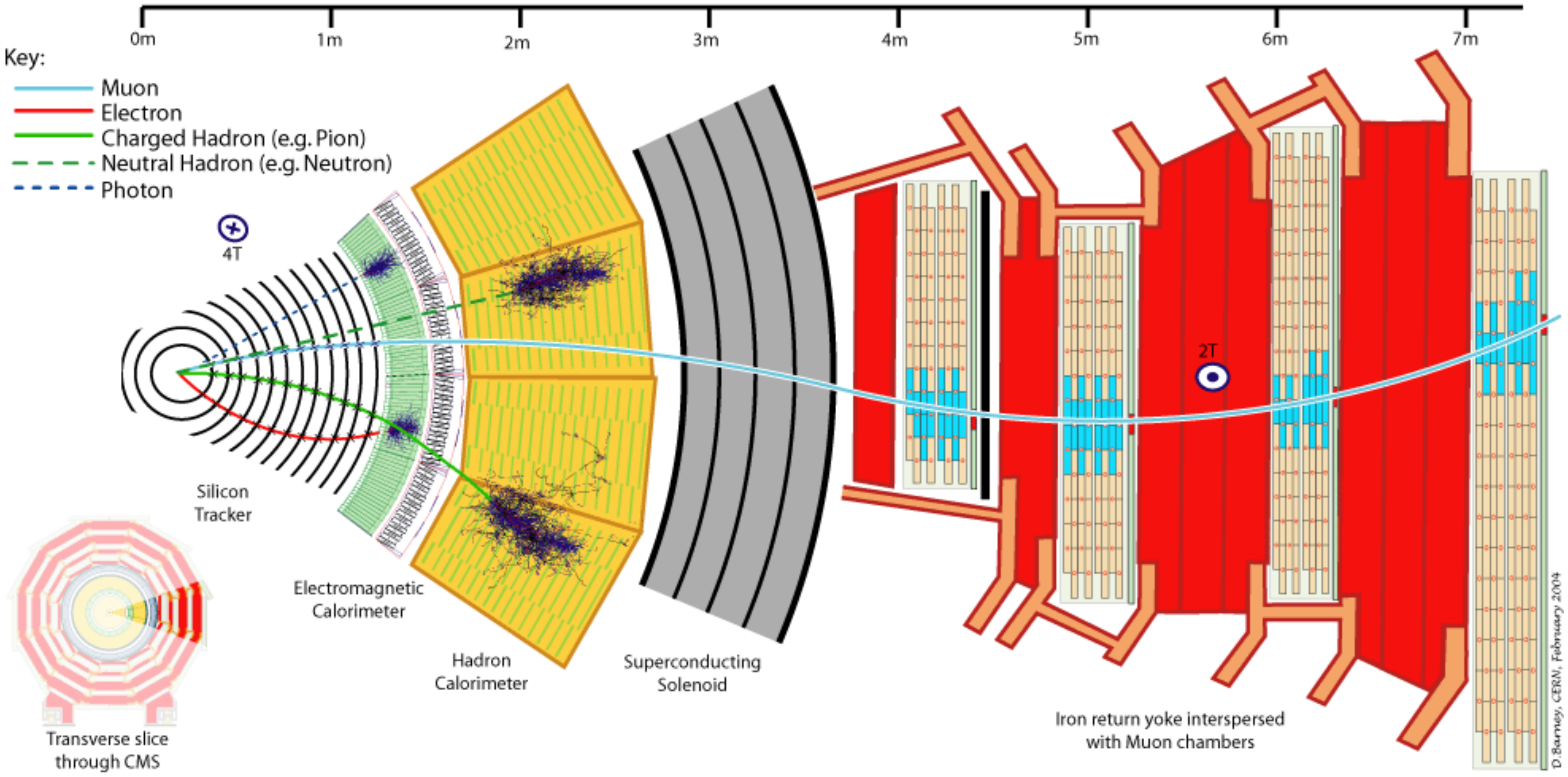
- I rivelatori di particelle sono costituiti da un insieme di sotto-rivelatori diversi.
- Le tecniche di rivelazione descritte precedentemente dettano una struttura a strati cilindrici concentrici dei rivelarori.
- Procedendo dall'asse del cilindro verso l'esterno tipicamente abbiamo:
  - un tracciatore immerso in un campo magnetico uniforme;
  - un "calorimetro elettromagnetico" per misurare l'energia degli elettroni e dei fotoni;
  - un "calorimetro adronico" per misurare l'energia degli adroni;
  - "rivelatori di posizione" per rivelare il passaggio dei muoni.

Come?



Identificazione delle particelle

- Quindi, disponendo i rivelatori in un certo ordine e combinandone le informazioni, è possibile identificare diversi tipi di particelle:
  - fotone: energia nel calorimetro elettromagnetico;
  - elettrone: traccia + energia nel calorimetro elettromagnetico;
  - muone: traccia + segnale nei rivelatori di muoni;
  - adrone carico: traccia + energia nel calorimetro adronico;
  - adrone neutro: energia nel calorimetro adronico.

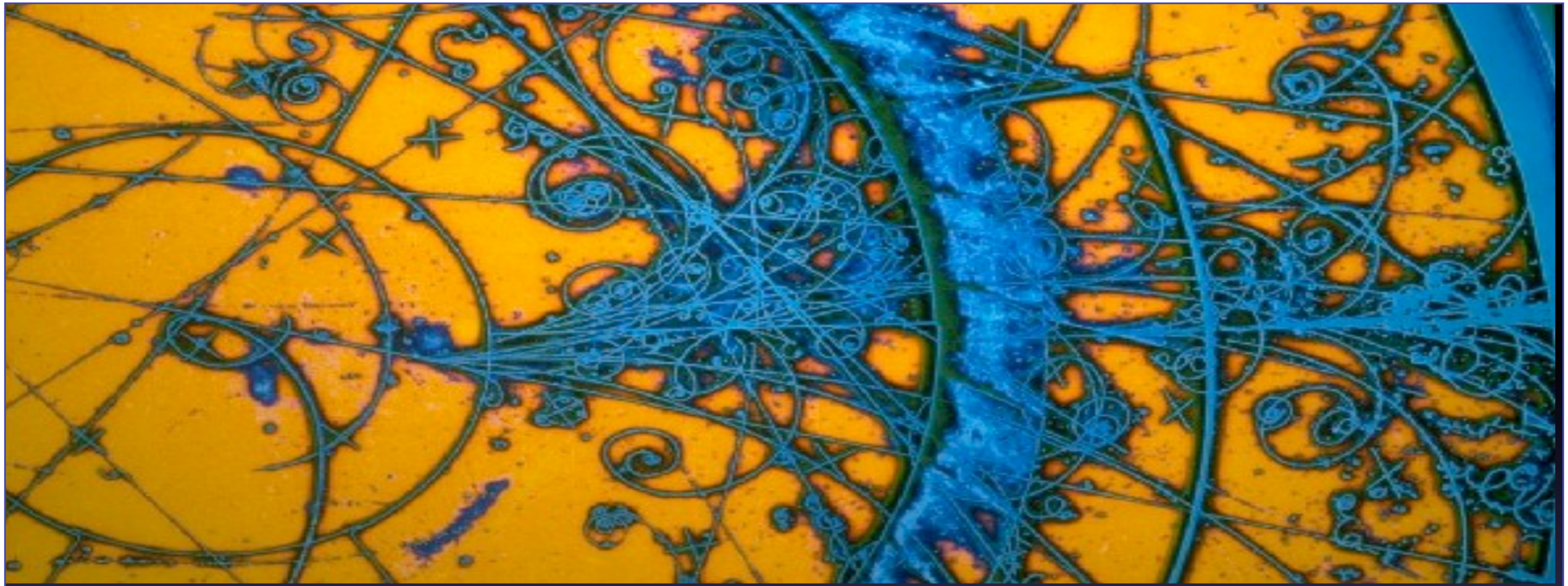

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

The Physics of Particle Detectors

Lecture Notes

SS 2012

Erika Garutti



Detectors for Particle Physics

Interaction with Matter

D. Bortoletto
University of Oxford

Detecting particles

- Every effect of particles or radiation can be used as a working principle for a particle detector.

Claus Grupen

Particle Detectors

Summer Student Lectures 2010

Werner Riegler, CERN, werner.riegler@cern.ch

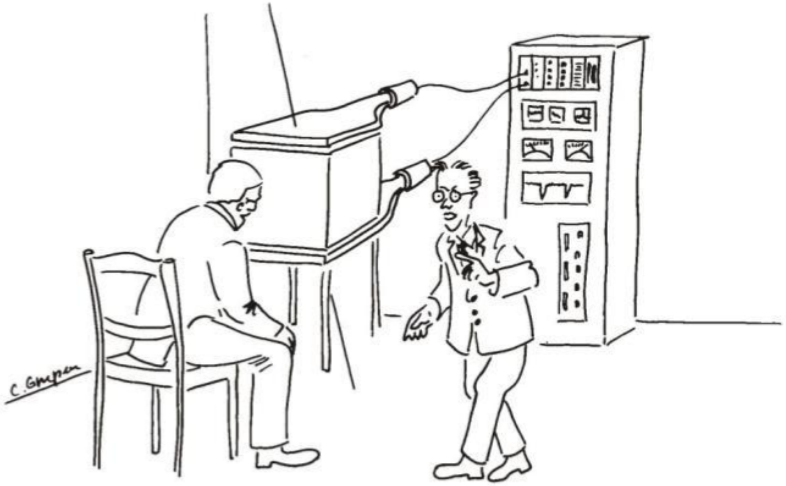
- History of Instrumentation ↔ History of Particle Physics
- The ‘Real’ World of Particles
- Interaction of Particles with Matter
- Tracking Detectors, Calorimeters, Particle Identification
- Detector Systems

Interaction of Particles with Matter

Any device that is to detect a particle must interact with it in some way → almost …

In many experiments neutrinos are measured by missing transverse momentum.

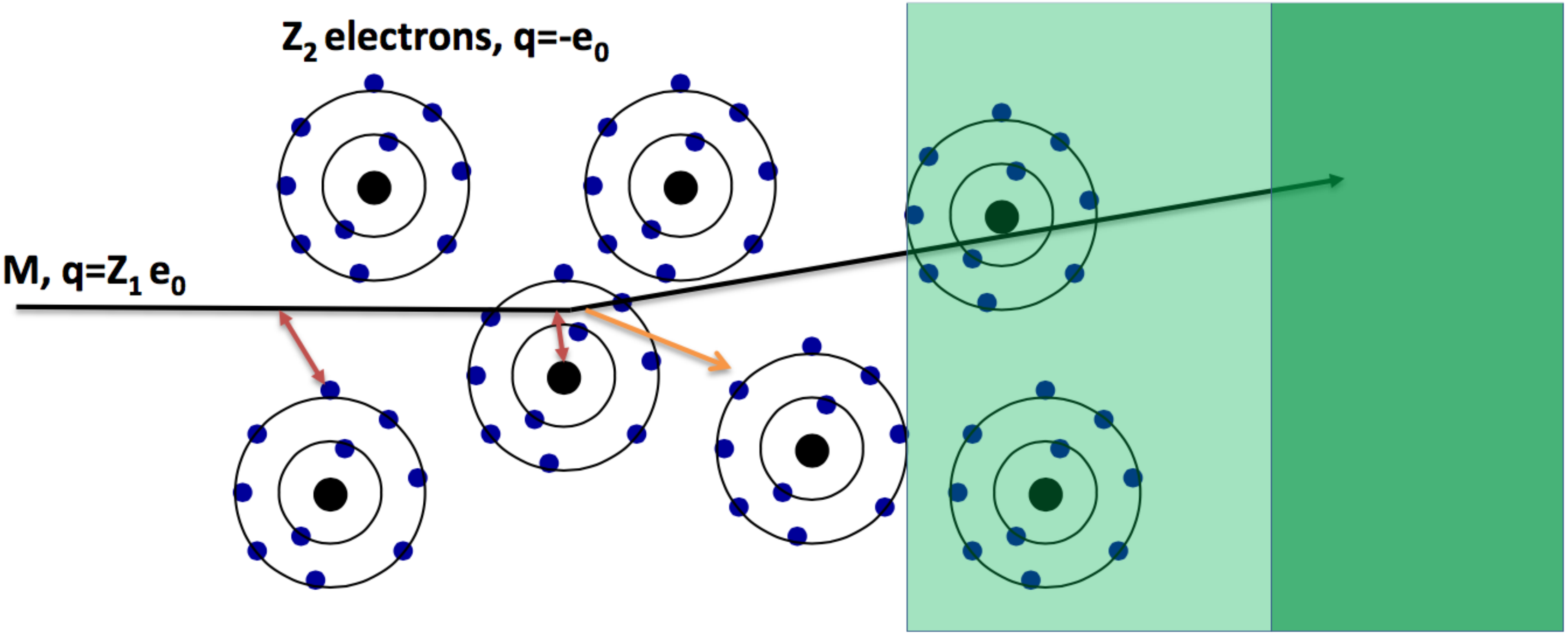
E.g. e^+e^- collider. $P_{tot}=0$,
If the $\Sigma\, p_i$ of all collision products is $\neq 0$ → neutrino escaped.



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

Electromagnetic Interaction of Particles with Matter



Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Astrofisica Nucleare e Subnucleare

Ionizzazione

Bethe Bloch Formula

$$\frac{1}{\rho}\frac{dE}{dx} = -4\pi r_e^2\, m_e c^2\, \frac{Z_1^2}{\beta^2}\, N_A \frac{Z}{A}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 F}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Für Z>1, I ≈16Z $^{0.9}$ eV

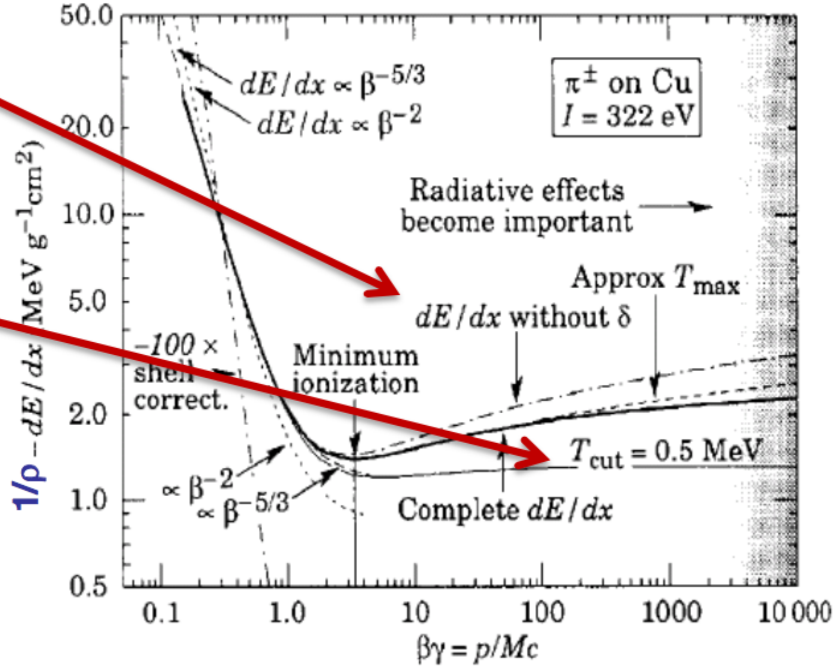
For Large βγ the medium is being polarized by the strong transverse fields, which reduces the rise of the energy loss → density effect

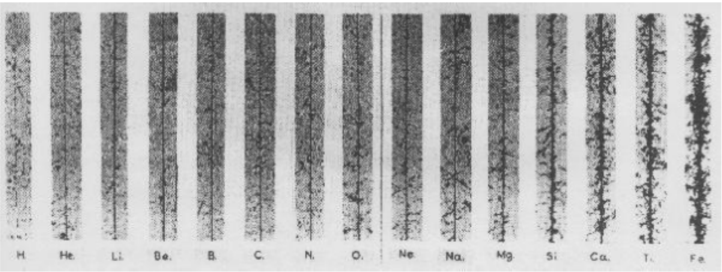
At large Energy Transfers (delta electrons) the liberated electrons can leave the material. In reality, E_{max} must be replaced by E_{cut} and the energy loss reaches a plateau (Fermi plateau).

Characteristics of the energy loss as a function of the particle velocity (βγ)

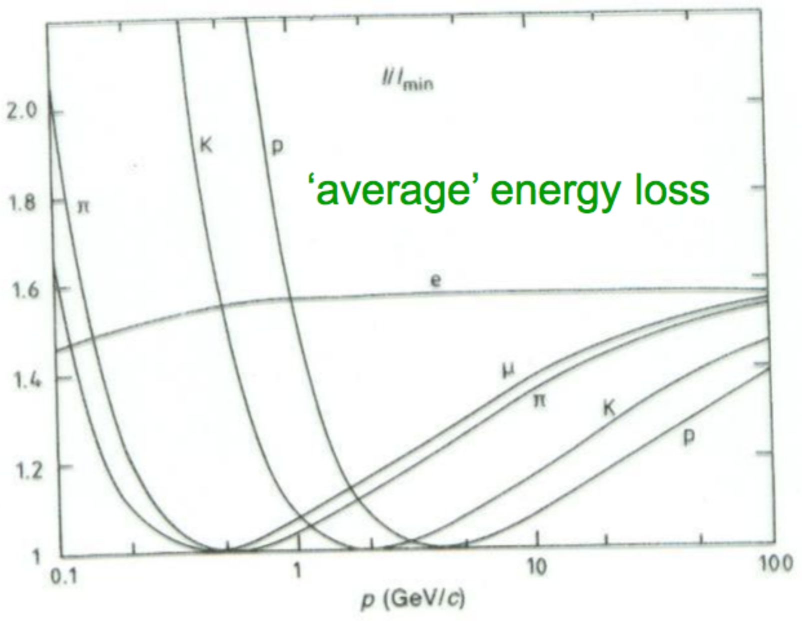
The specific Energy Loss 1/ρ dE/dx

- **first decreases as $1/\beta^2$**
- **increases with ln γ for β =1**
- **is ≈ independent of M ($M \gg m_e$)**
- **is proportional to Z_1^2 of the incoming particle.**
- **is ≈ independent of the material (Z/A ≈ const)**
- **shows a plateau at large βγ (>>100)**
- **dE/dx ≈ 1-2 x ρ [g/cm³] MeV/cm**

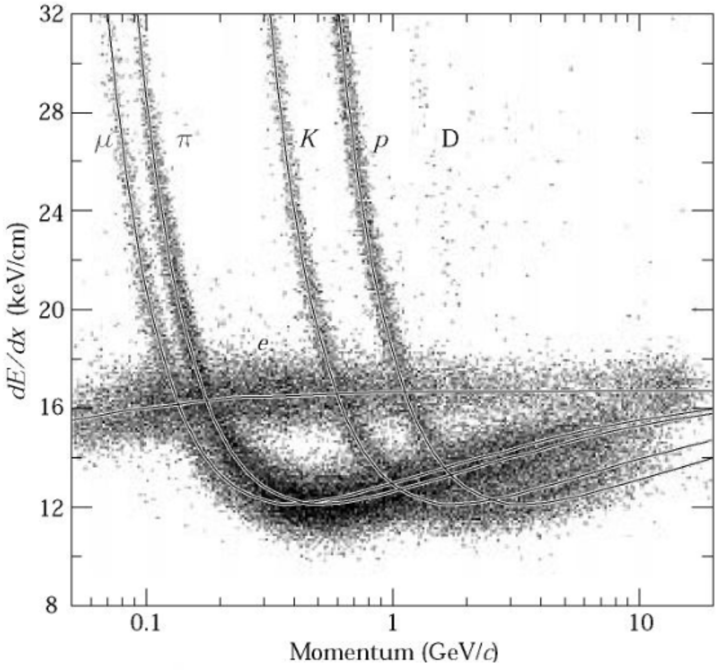




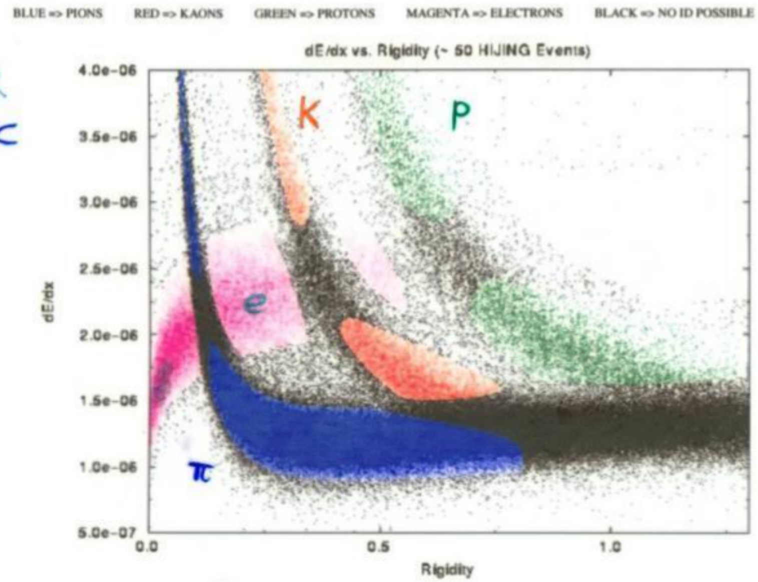
Particle Identification


'average' energy loss

Measured energy loss

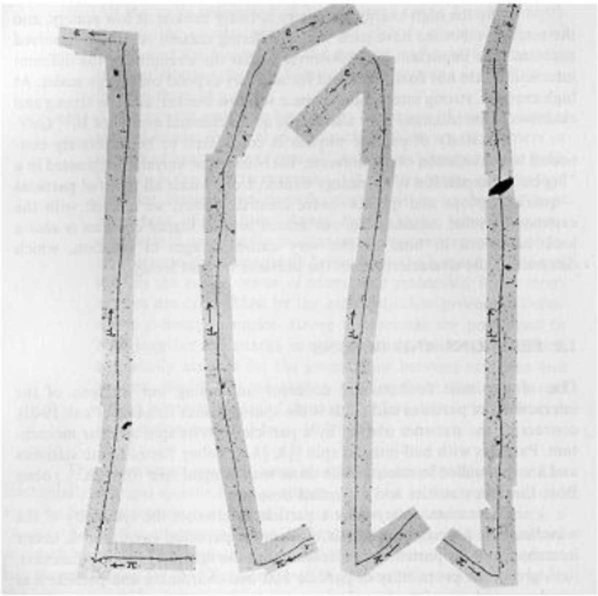


STAR TPC

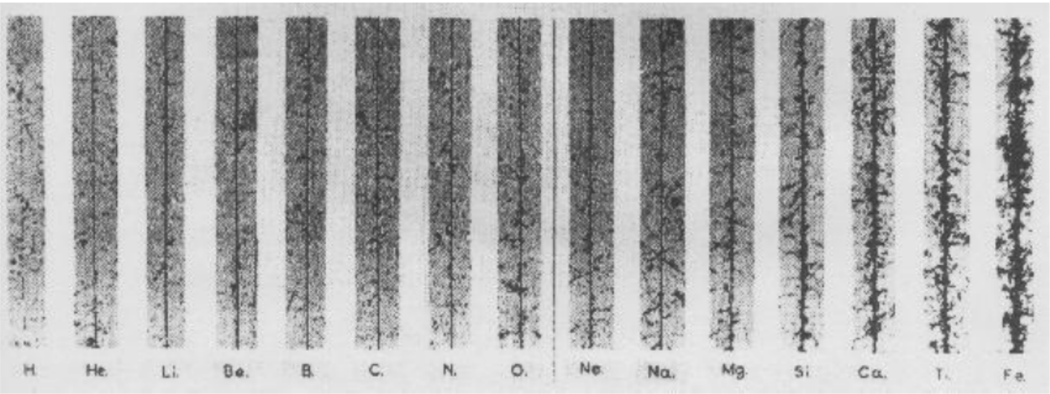


In certain momentum ranges, particles can be identified by measuring the energy loss.

Small energy loss
→ Fast Particle

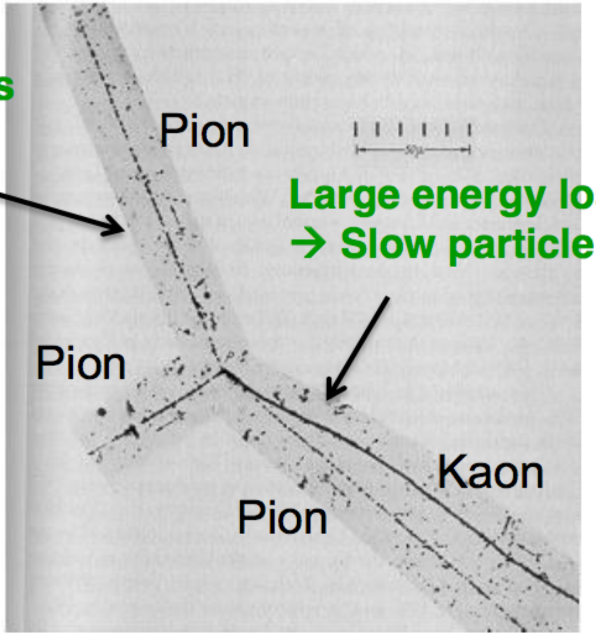


Discovery of muon and pion



Cosmis rays: dE/dx α Z^2

Small energy loss
→ Fast particle



Large energy loss
→ Slow particle

Range of Particles in Matter

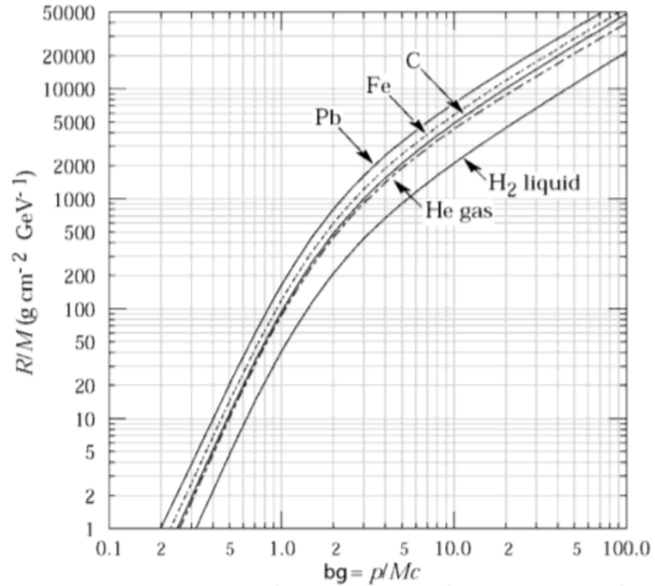
Particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at distance R.

$$R(E_0) = \int_{E_0}^{0} \frac{-1}{dE/dx} dE$$

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho} \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

$$\frac{\rho}{Mc^2} R(\beta_0\gamma_0) = \frac{1}{Z_1^2} \frac{A}{Z} f(\beta_0\gamma_0)$$

≈Independent of the material

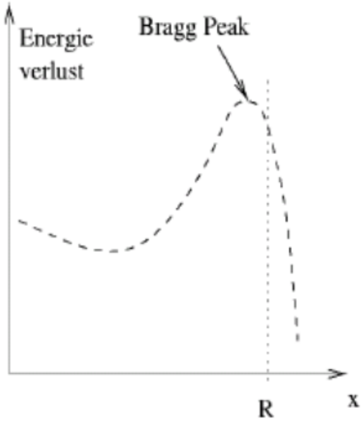


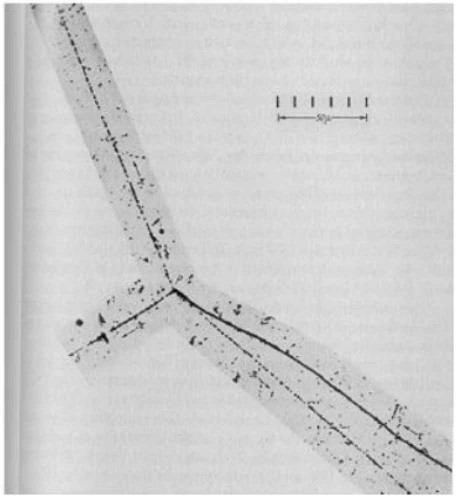
Bragg Peak:

For βγ>3 the energy loss is ≈ constant (Fermi Plateau)

If the energy of the particle falls below βγ=3 the energy loss rises as $1/\beta^2$

Towards the end of the track the energy loss is largest → Cancer Therapy.



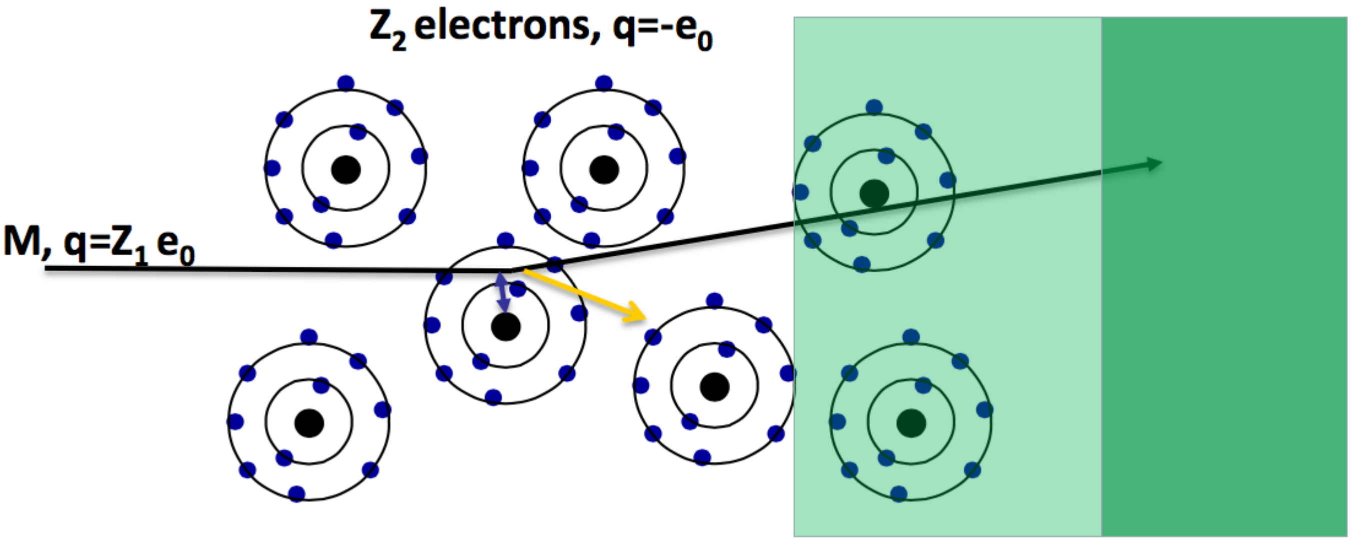


Astrofisica Nucleare e Subnucleare

Bremsstrahlung

Bremsstrahlung

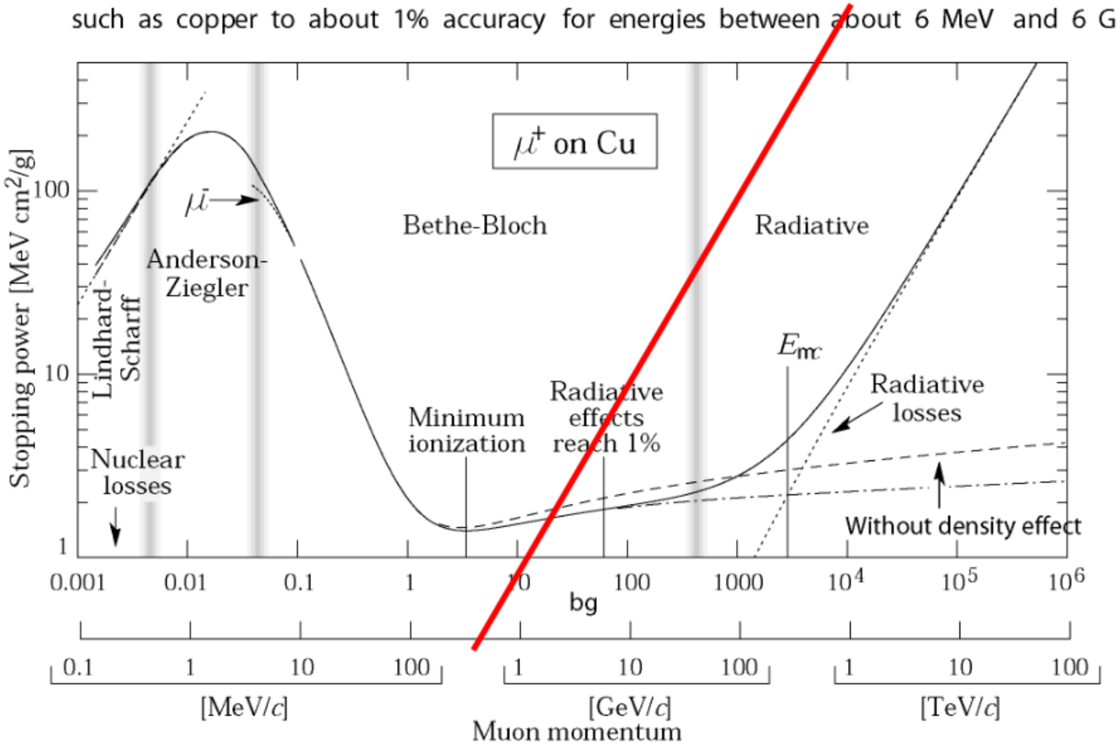
A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of charge Ze which is partially 'shielded' by the electrons. During this deflection the charge is 'accelerated' and it therefore radiated → Bremsstrahlung.



7/15/2010

Critical Energy

such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV



Electron Momentum 5 50 500 MeV/c

For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

Critical Energy: If dE/dx (Ionization) = dE/dx (Bremsstrahlung)

Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Astrofisica Nucleare e Subnucleare

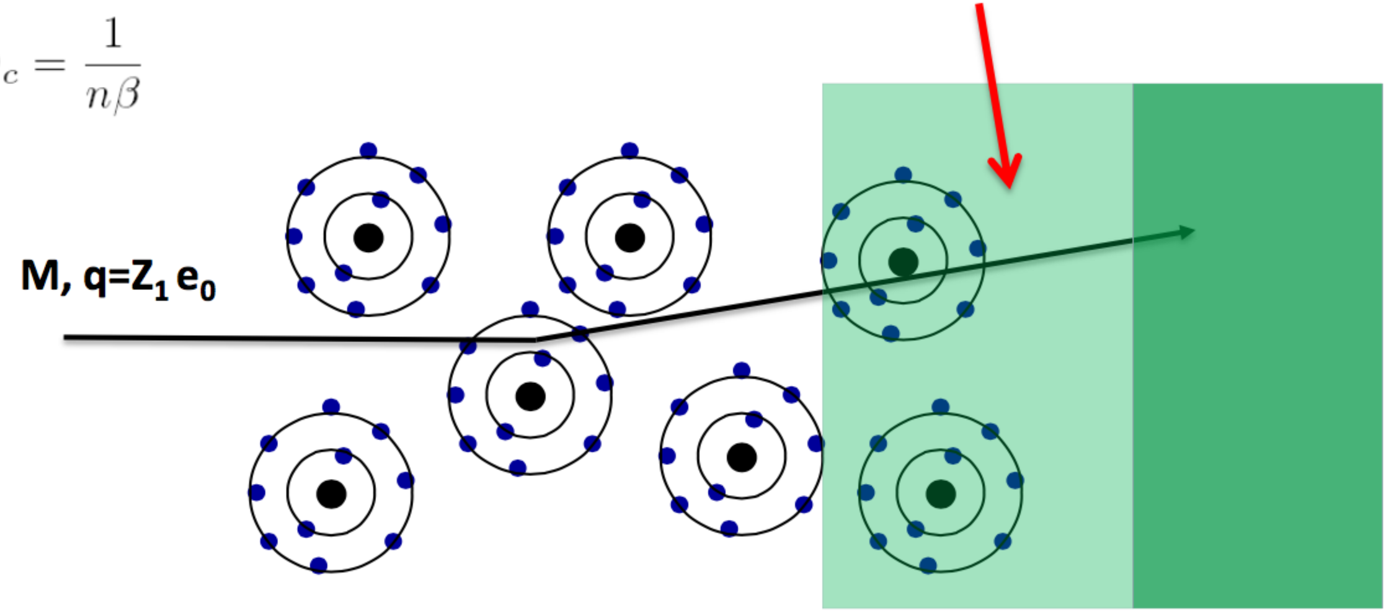
Effetto Cherenkov

Cherenkov Radiation

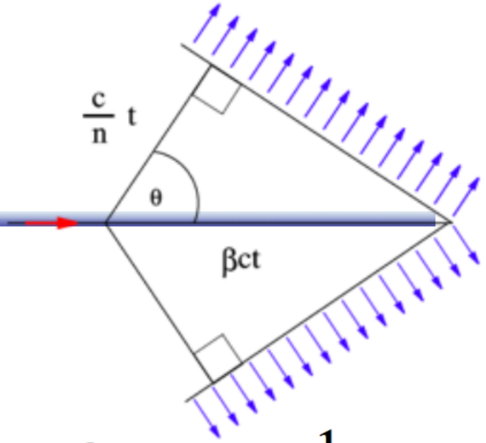
If we describe the passage of a charged particle through material of dielectric permittivity ♏ (using Maxwell's equations) the differential energy crossection is >0 if the velocity of the particle is larger than the velocity of light in the medium

N is the number of Cherenkov Photons emitted per cm of material. The expression is in addition proportional to Z_1^2 of the incoming particle.
The radiation is emitted at the characteristic angle ❑$_c$, that is related to the refractive index n and the particle velocity by

$$\cos\Theta_c = \frac{1}{n\beta}$$



Cherenkov radiation



Velocity of the particle: v
Velocity of light in a medium of refractive index n: c/n

Threshold condition for Cherenkov light emission: $v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$

$$-\left\langle \frac{dE}{dx} \right\rangle_{Cherenkov} \propto z^2 \sin^2 \theta_c \qquad \cos\theta_c = \frac{1}{n\beta}$$

for water $\theta_c^{max} = 42°$
for neon at 1 atm $\theta_c^{max} = 11\text{mrad}$

Energy loss by Cherenkov radiation very small w.r.t. ionization (< 1%)

Typically O(1-2 keV / cm) or O(200-1000) visible photons / cm

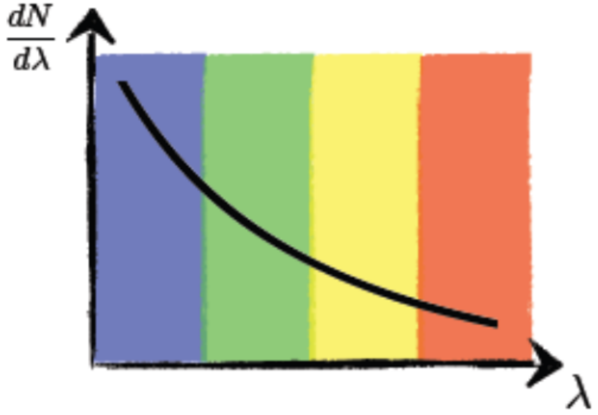
Visible photons:
E = 1 - 5 eV; λ = 300 - 600 nm

Cherenkov radiation

In a Cherenkov detector the produced photons are measured

Number of emitted photons per unit of length:

- wavelength dependence ~ $1/\lambda^2$



$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\boxed{\lambda^2}} \sin^2\theta_C$$

Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

$$= 475\, z^2 \sin^2\theta_C \text{ photons/cm}$$

- energy dependence ~ constant

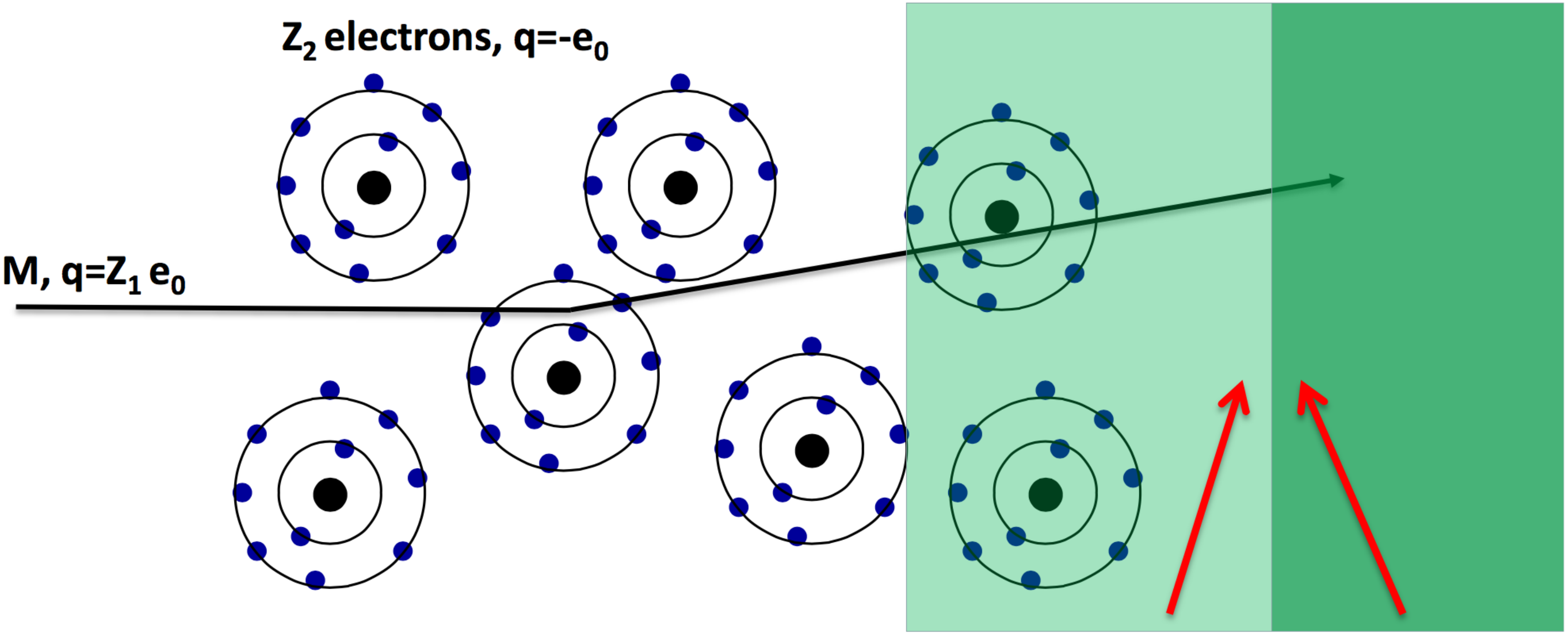
$$\frac{d^2N}{dEdx} = \frac{z^2\alpha}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{z^2\alpha}{\hbar c} \sin^2\theta_C$$

$$\approx \text{const}$$

$$\frac{d^2N}{dEdx} = 370 \sin^2\theta_C \text{ eV}^{-1} \text{ cm}^{-1}$$

Astrofisica Nucleare e Subnucleare
Radiazione di Transizione

Transition Radiation

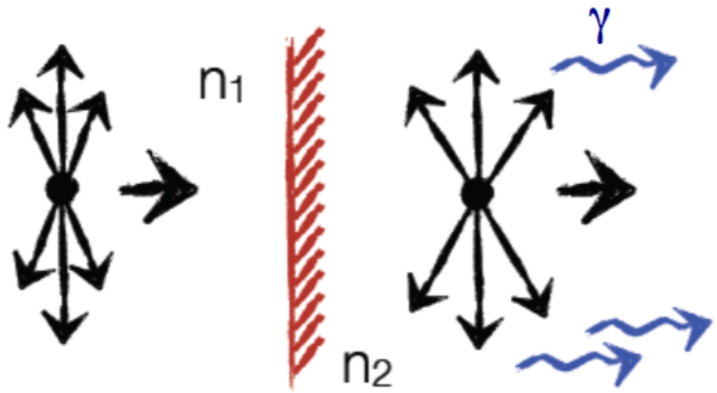


When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called <u>Transition radiation</u>.

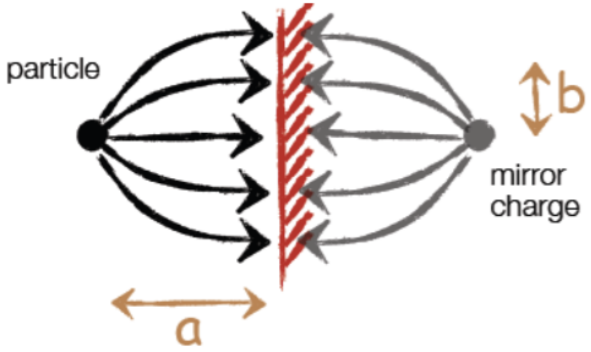
Transition Radiation

Transition radiation occurs if a relativist particle (large γ) passes the boundary between two media with different refraction indices ($n_1 \neq n_2$)
[predicted by Ginzburg and Frank 1946; experimental confirmation 70ies]

Effect can be explained by
re-arrangement of electric field:



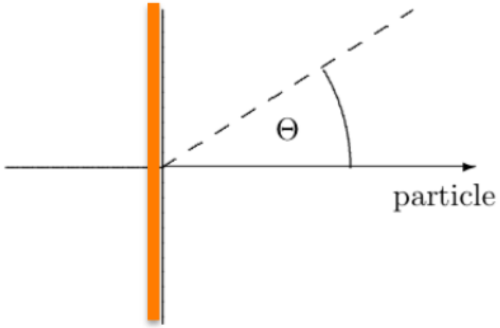
A charged particle approaching a boundary created a magnetic dipole with its mirror charge



The time-dependent dipole field causes the emission of electromagnetic radiation

Energy radiated from a single boundary: $S = \frac{1}{3}\alpha z^2 \gamma \hbar\omega_P \quad (\hbar\omega_P \approx 20 eV)$

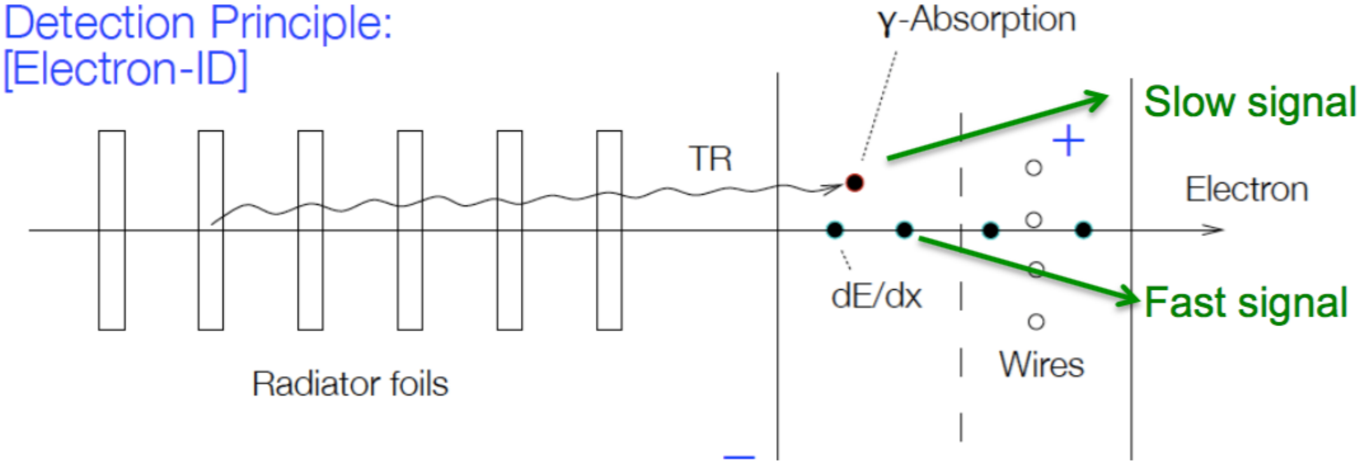
Transition Radiation



- Typical emission angle: $\Theta = 1/\gamma$
- Energy of radiated photons: $\sim \gamma$
- Number of radiated photons: αz^2
- Effective threshold: $\gamma > 1000$

➔ Use stacked assemblies of low Z material with many transitions + a detector with high Z gas

Detection Principle:
[Electron-ID]



Note: Only X-ray (E>20keV) photons can traverse the many radiators without being absorbed

Astrofisica Nucleare e Subnucleare

Multiple Scattering

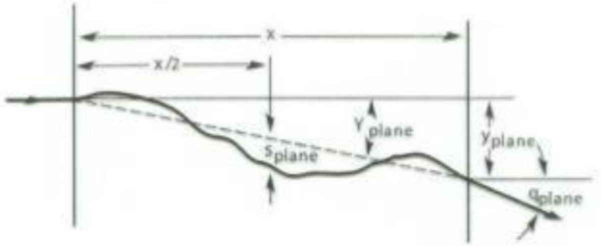
Multiple Scattering

Statistical (quite complex) analysis of multiple collisions gives:

Probability that a particle is defected by an angle θ after travelling a distance x in the material is given by a Gaussian distribution with sigma of:

$$\Theta_0 = \frac{0.0136}{\beta c p[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

X_0 ... Radiation length of the material
Z_1 ... Charge of the particle
p ... Momentum of the particle



Astrofisica Nucleare e Subnucleare

Interazione di Fotoni

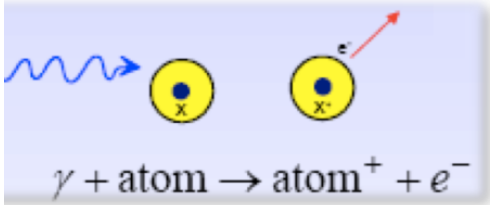
Interactions of photons with matter

Characteristic for interactions of photons with matter:

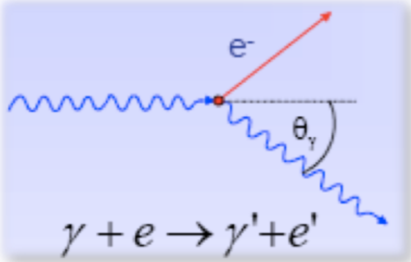
A photon is removed from the beam after one single interaction

either because of total absorption or scattering

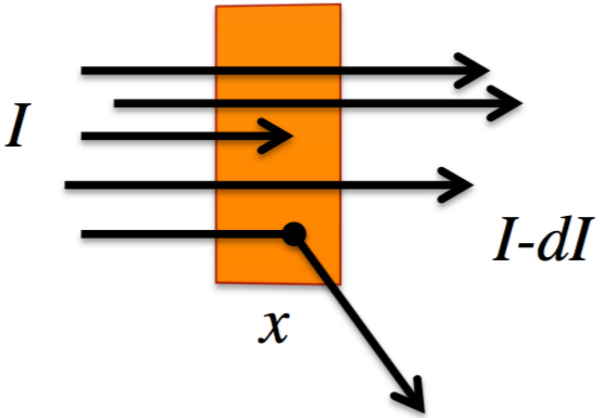
) Photoelectric Effect 2) Compton Scattering



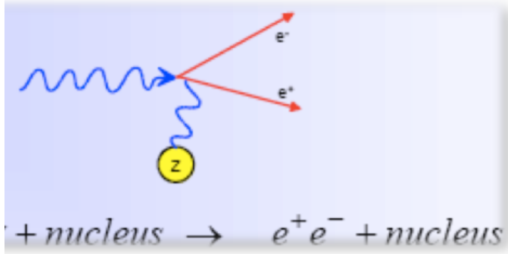
$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$



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



3) Pair Production



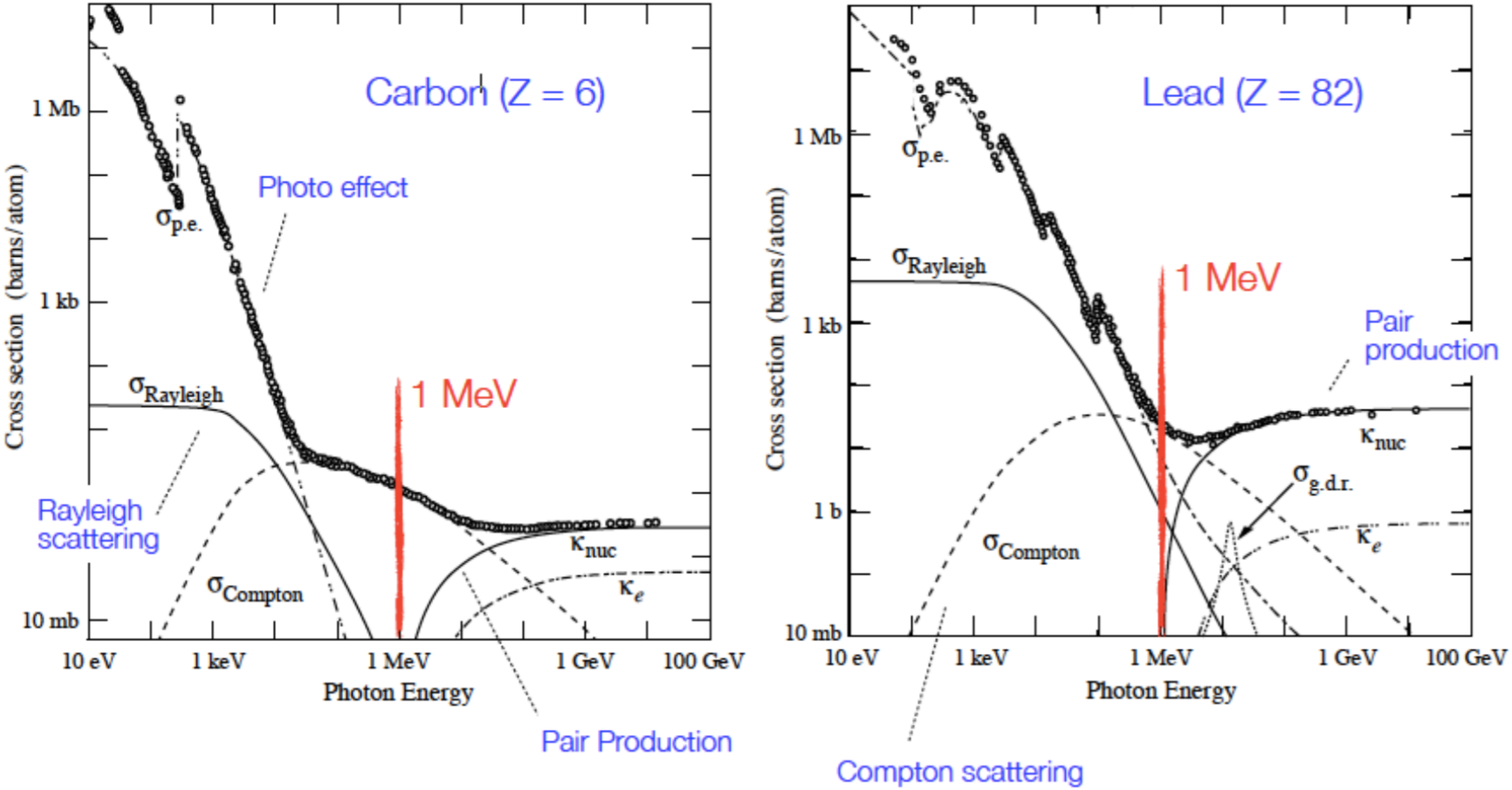
$\gamma + nucleus \rightarrow e^{+}e^{-} + nucleus$

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

$$\lambda = 1/\mu$$ Mean free path

Interactions of photons with matter

Photon Total Cross Sections

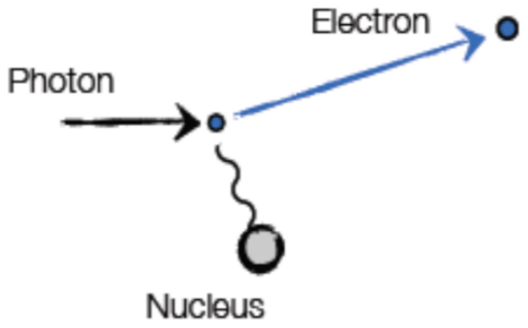


Photoelectric effect

From energy conservation:

$$E_e = E_\gamma - E_N = h\upsilon - I_b$$

I_b = Nucleus binding energy
introduces strong Z dependence



Naive picture

Cross-section largest for $E_\gamma \approx$ K-shell energy
Strongest E dependence for $I_0 < E_\gamma < m_e c^2$

$$\sigma_{ph} = \alpha\pi a_B \boxed{Z^5} (I_0 / \boxed{E_\gamma)^{7/2}}$$

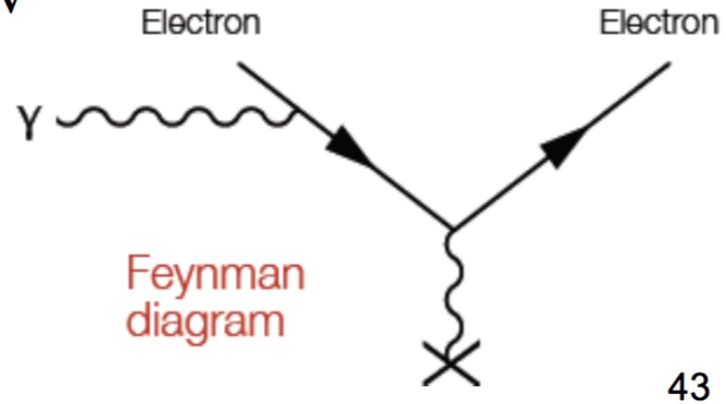
$$a_B = 0.53\ \dot{\mathrm{A}}$$

$$I_0 = 13.6\ \mathrm{eV}$$

γ + atom → e^- + atom$^+$

E-dependence softer for $E_\gamma > m_e c^2$

$$\sigma_{ph} = 2\pi r_e^2 \alpha^4 Z^5 (mc)^2 / E_\gamma$$



Feynman diagram

Compton scattering

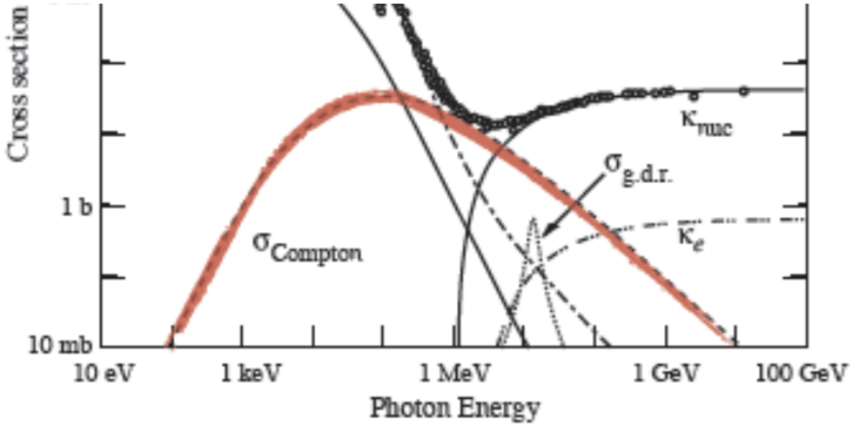
Best known electromagnetic process (Klein–Nishina formula)

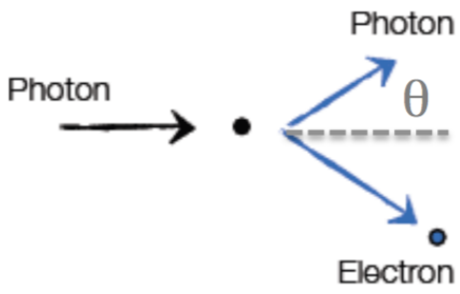
$$\text{for } E_\lambda << m_e c^2 \quad \boxed{\sigma_c \propto \sigma_{Th}(1-2\varepsilon)}$$

Thompson cross-section:
$\sigma_{Th} = 8\pi/3\ r_e^2 = 0.66$ barn

$$\varepsilon = \frac{E_\lambda}{m_e c^2}$$

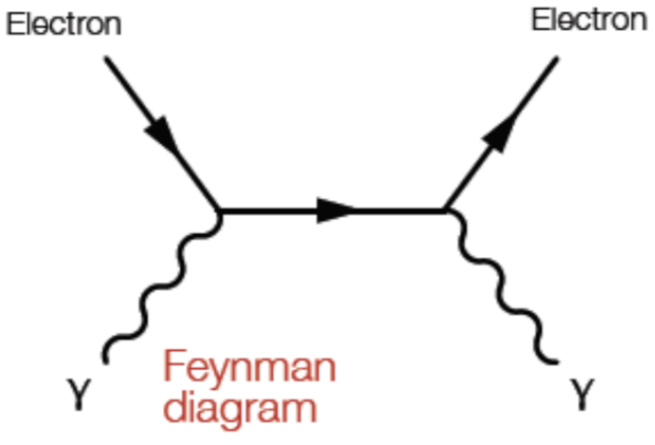
$$\text{for } E_\lambda >> m_e c^2 \quad \boxed{\sigma_c \propto \frac{\ln \varepsilon}{\varepsilon} Z}$$





Naive picture

$\gamma + e^- \rightarrow (\gamma)' + (e^-)'$



Feynman diagram

Compton scattering

From E and p conservation get the energy of the scattered photon

$$E_\gamma' = \frac{E_\gamma}{1+\varepsilon(1-\cos\theta)} \qquad \varepsilon = \frac{E_\lambda}{m_e c^2}$$

Kinetic energy of the outgoing electron:

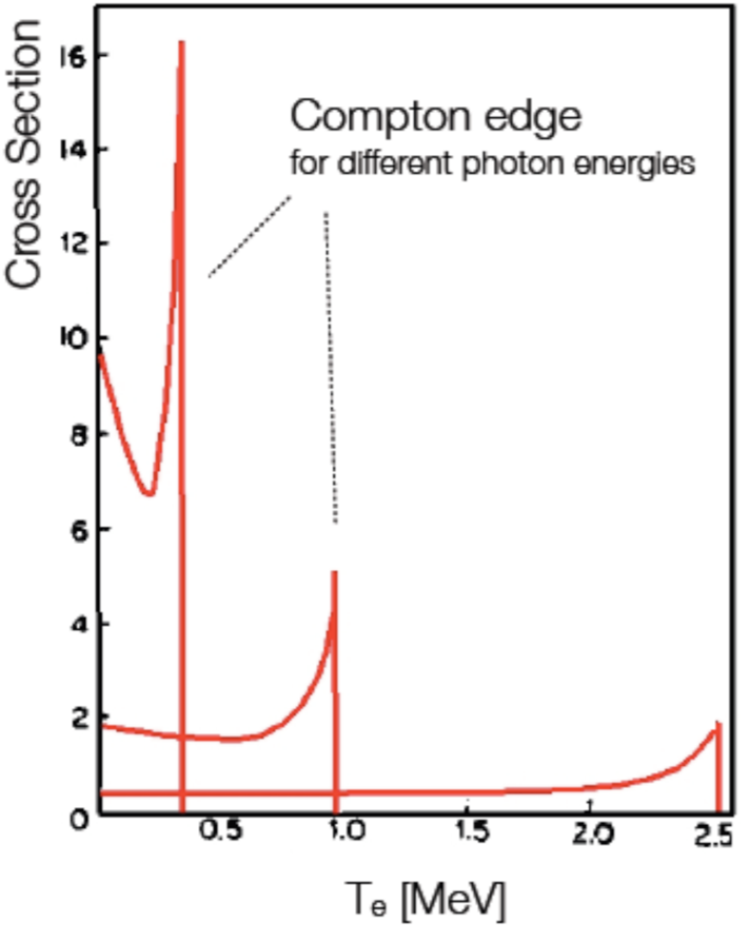
$$T_e = E_\gamma - E_\gamma' = E_\gamma \frac{\varepsilon(1-\cos\theta)}{1+\varepsilon(1-\cos\theta)}$$

Max. electron recoil energy for $\theta = \pi$:

$$\boxed{T_{\max} = E_\gamma \frac{2\varepsilon}{1+2\varepsilon}}$$

Transfer of complete γ-energy via Compton scattering not possible:

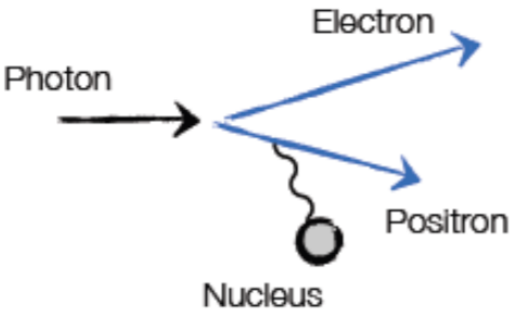
$$\Delta E = E_\gamma - T_{\max} = E_\gamma \frac{1}{1+2\varepsilon}$$

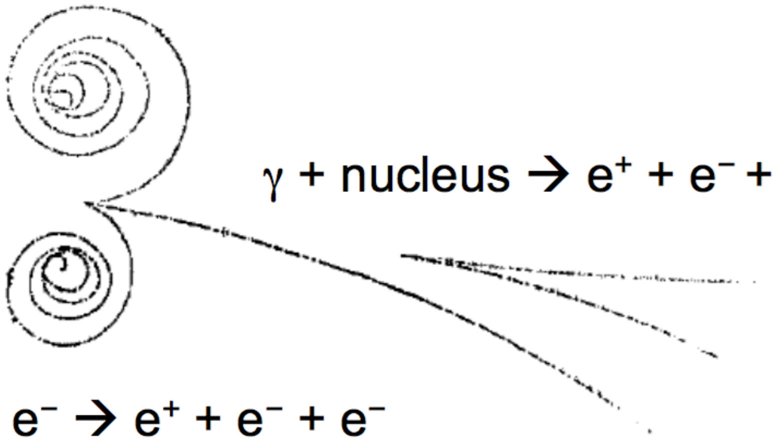


Pair production

Minimum energy required for this process
2 m_e + Energy transferred to the nucleus

$$E_\gamma \geq 2m_ec^2 + \frac{2m_ec^2}{m_{Nucleus}}$$

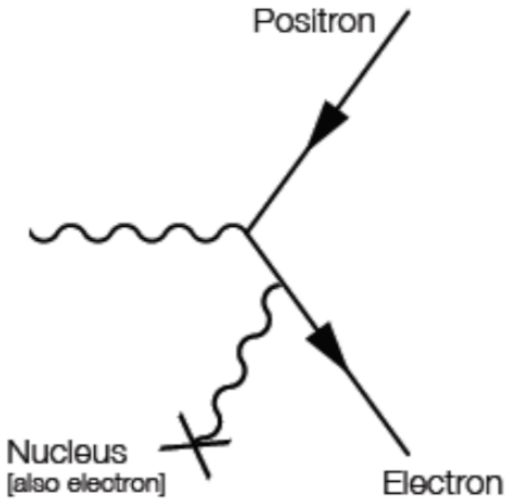




γ + nucleus → $e^+ + e^- +$ nucleus’

$\gamma + e^- \rightarrow e^+ + e^- + e^-$

γ + atom → $e^+ + e^-$



Pair production

for $E_\lambda >> m_e c^2$ $$\sigma_{\text{pair}} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \quad [\text{cm}^2/\text{atom}]$$

Using as for Bremsstrahlung the radiation length

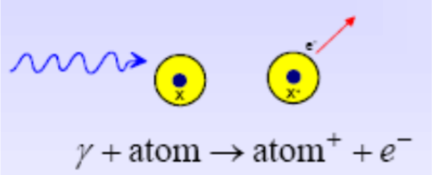
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

$$\boxed{\sigma_{pair} = \frac{7}{9} \frac{N_A}{A} \cdot \frac{1}{X_0}}$$

	ρ [g/cm³]	X_0 [cm]
H_2 [fl.]	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Luft	$1.2 \cdot 10^{-3}$	$30 \cdot 10^{3}$

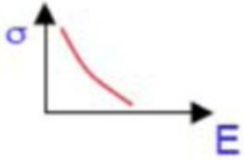
Electromagnetic interactions

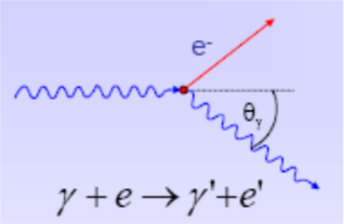
Gammas



$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$

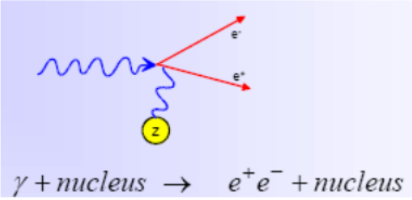
- Photoelectric effect





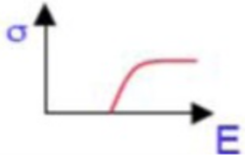
$\gamma + e \rightarrow \gamma' + e'$

- Compton effect



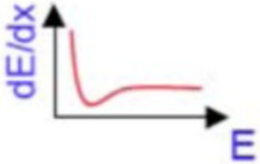
$\gamma + nucleus \rightarrow e^+e^- + nucleus$

- Pair production

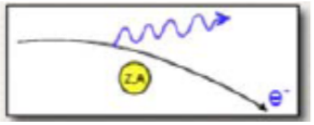


Electrons

- Ionisation



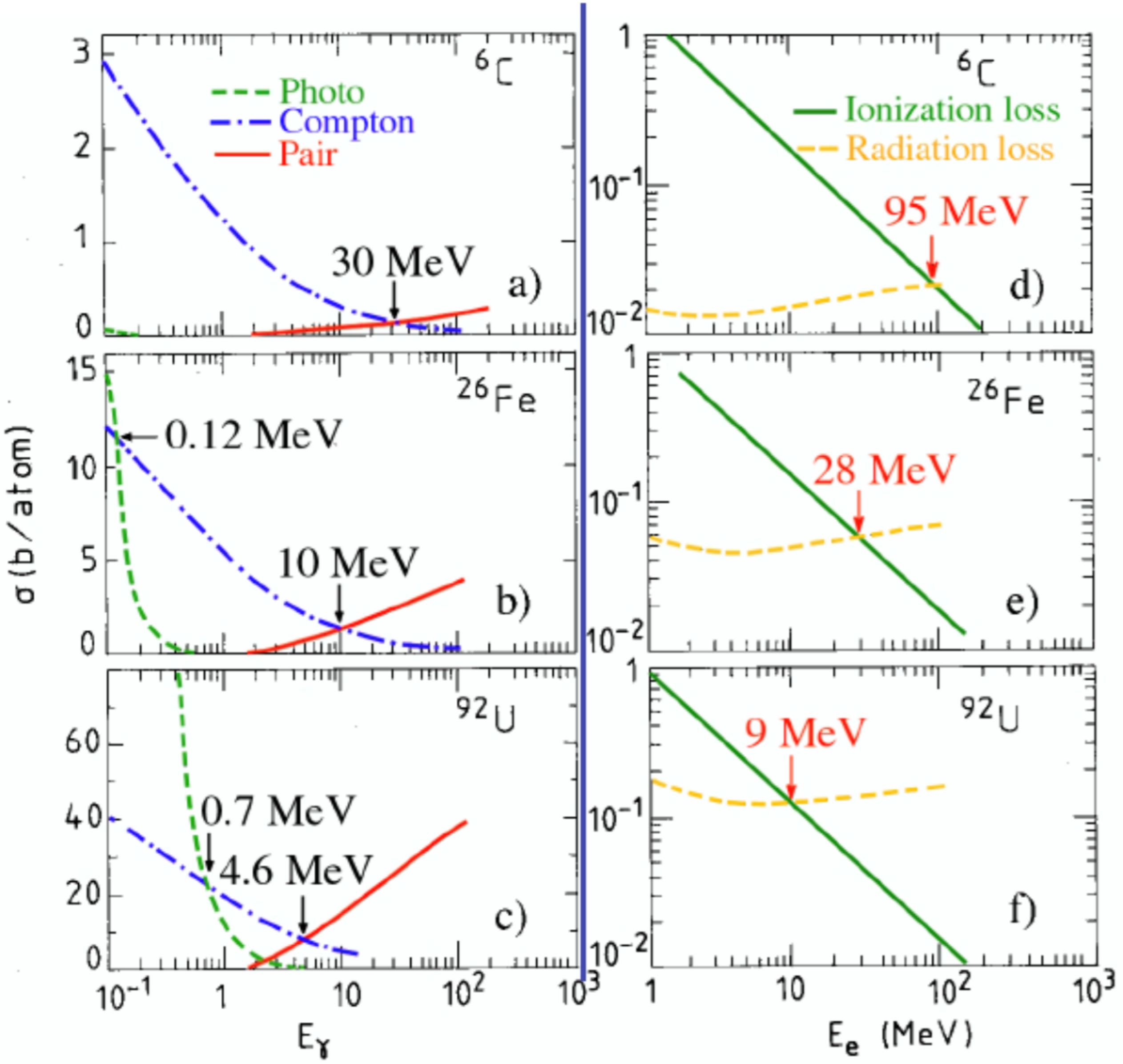
- Bremsstrahlung



Material dependence

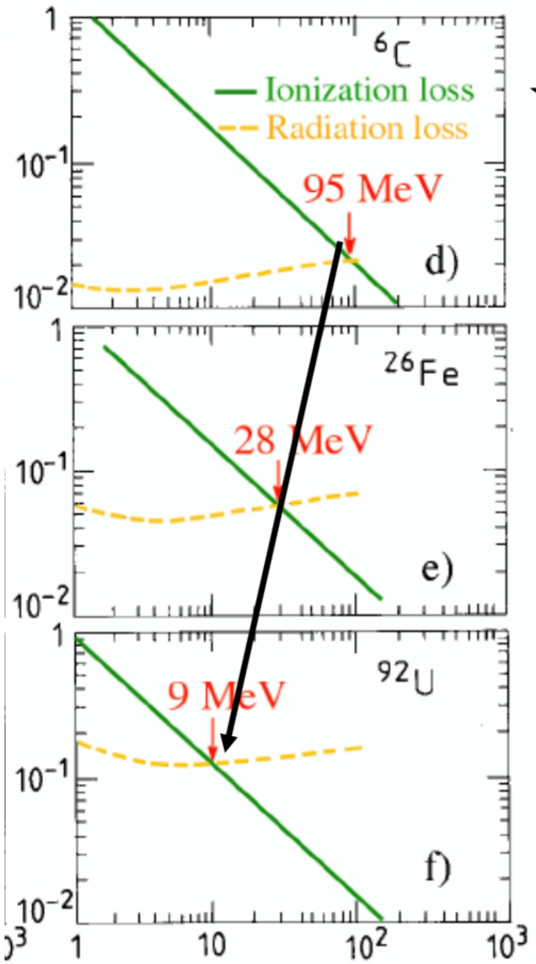
Increasing Z

Gammas



Electrons

Electrons



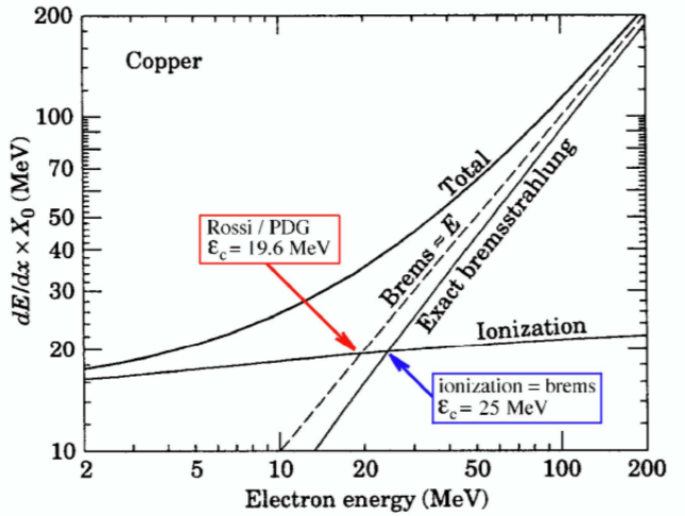
Increasing Z

Electrons lose energy by: *ionization* *radiation*

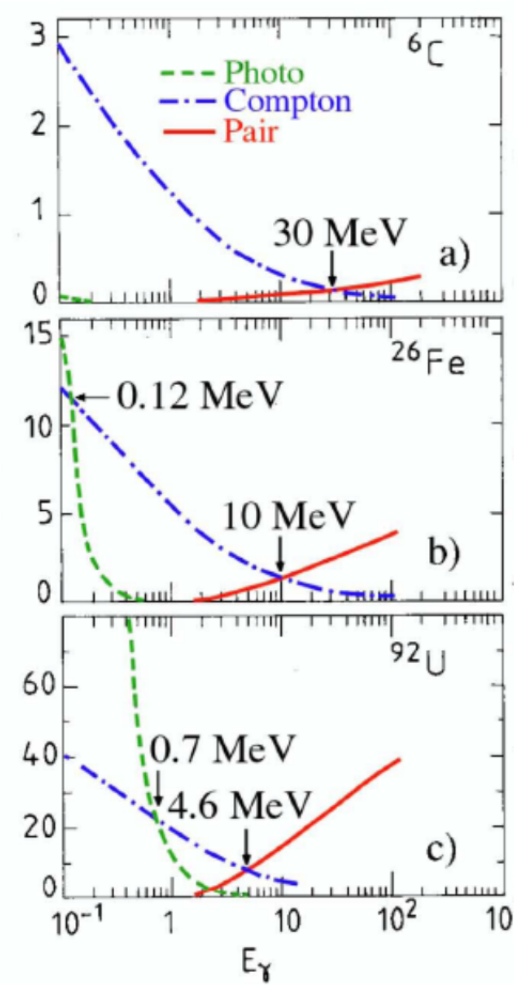
Critical energy ϵ_c: $\frac{dE}{dx}$ (ion) $=$ $\frac{dE}{dx}$ (rad)

$\epsilon_c \propto 1/Z$ PDG: $\epsilon_c = 610\ \mathrm{MeV}/(Z + 1.24)$

In high Z materials
particle multiplication
at lower energies



Photons



Increasing Z

- *Photons* interact by:

1) *Photoelectric* effect $\sigma \propto Z^5,\ E^{-3}$

2) *Compton* scattering $\sigma \propto Z,\ E^{-1}$

3) *Conversion* into e^+e^- σ increases with E, Z, asymptotic at ~ 1 GeV

Astrofisica Nucleare e Subnucleare

Sciami Elettromagnetici

ELECTROMAGNETIC SHOWERS
SCIAMI ELETTTROMAGNETICI

$$-\frac{dE}{dX} \simeq \frac{E}{X_0}$$

SIA $e^{\pm}$ CHE γ

$$E = E_i e^{-\frac{X}{X_0}}$$

ΔX DOPO UNA LUNGHEZZA DI RADIAZIONE $= X_0$
(AFTER ONE RADIATION LENGTH)

$$-dE = \frac{E\,dX}{X_0} \qquad \Delta E \simeq E\frac{\Delta X}{X_0} \simeq E$$

RADIAZIONE
(RADIATION) $e^{\pm} \rightarrow e^{\pm}\gamma$ BREMSSTRAHLUNG

CONVERSIONE
(CONVERSION) $\gamma \rightarrow e^+e^-$ CREAZIONE COPPIE
(PAIR CREATION)

$$1 \rightarrow 2$$

$$E_i \rightarrow 2\left(\frac{E_i}{2}\right)$$

DOPO TANTE LUNGHEZZE DI RADIAZIONE
(AFTER MANY RADIATION LENGTHS)

$$X = t X_0 \qquad t = \frac{X}{X_0}$$

$$1 \rightarrow 2^t \equiv N$$

$$E_i \rightarrow 2^t\left(\frac{E_i}{2^t}\right) = N\left(\frac{E_i}{N}\right) = N E(t)$$

$$E(t) = \frac{E_i}{N} = \frac{E_i}{2^t}$$

QUANDO $E(t)$ ARRIVA A E_c
(WHEN) (REACHES)

DIVENTANO DOMINANTI : $\left(E = \frac{E_i}{N} = E_c\right)$
(BECOME DOMINANT)

PER $e^{\pm}$: IONIZZAZIONE

PER γ : COMPTON E FOTOELETTRICO

N SMETTE LA CRESCITA ESPONENZIALE

N RAGGIUNGE IL MASSIMO

$$N_{MAX} = \frac{E_i}{E_c}$$

$$N_{MAX} = 2^{t_{MAX}} = \frac{E_i}{E_c}$$

$$t_{MAX} = \ln \frac{E_i}{E_c} \cdot \frac{1}{\ln 2}$$

N POI DECRESCE PER PROGRESSIVA PERDITA DELLE ENERGIE RESIDUE

Fig. 4.6. The total number of particles N in a shower initiated by an electron of energy E_0, as a function of depth n, measured in radiation lengths; E_c is the critical energy of the material. (From Leighton, 1959, p. 693, after Rossi & Greisen, 1941.)