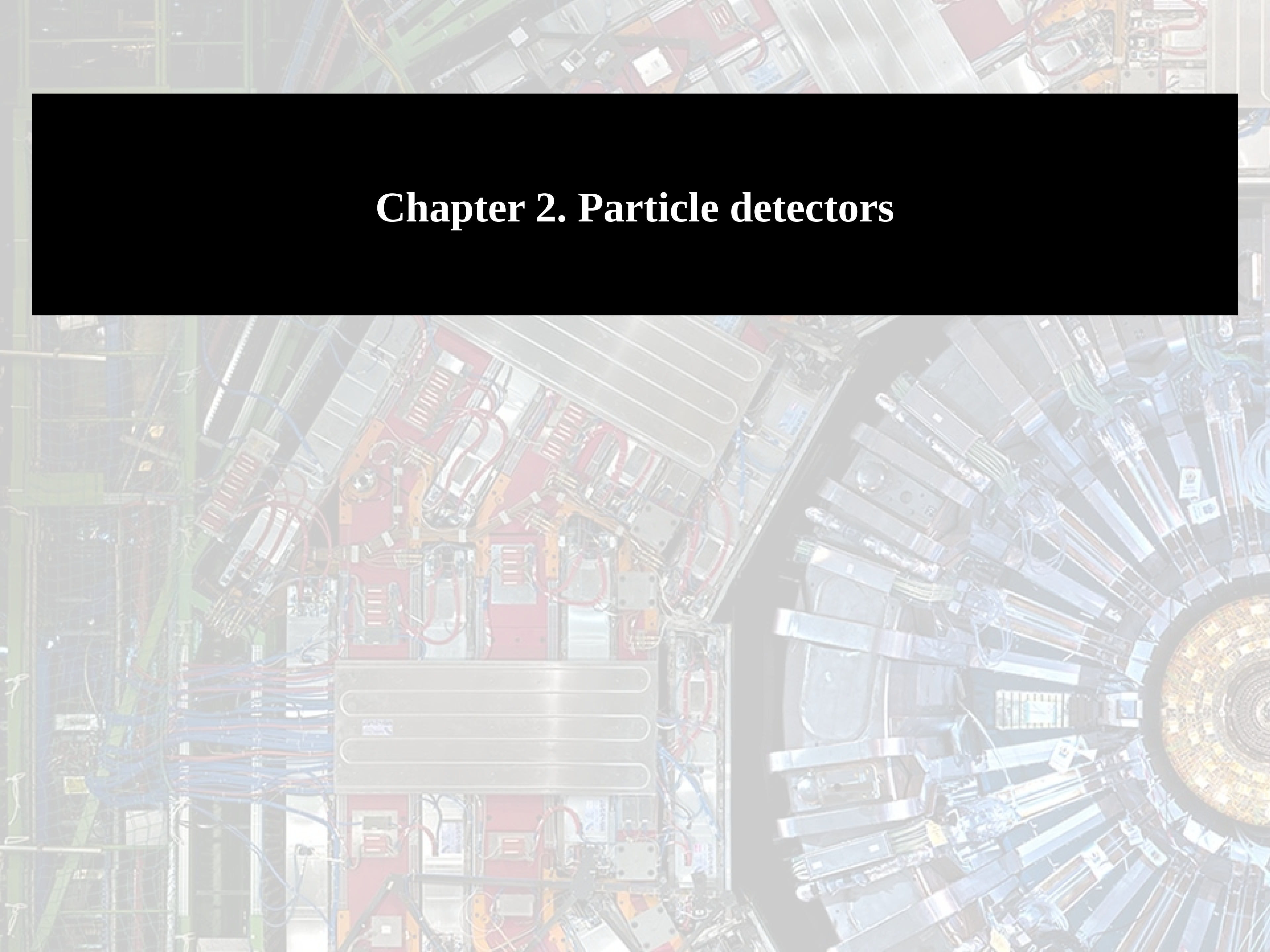
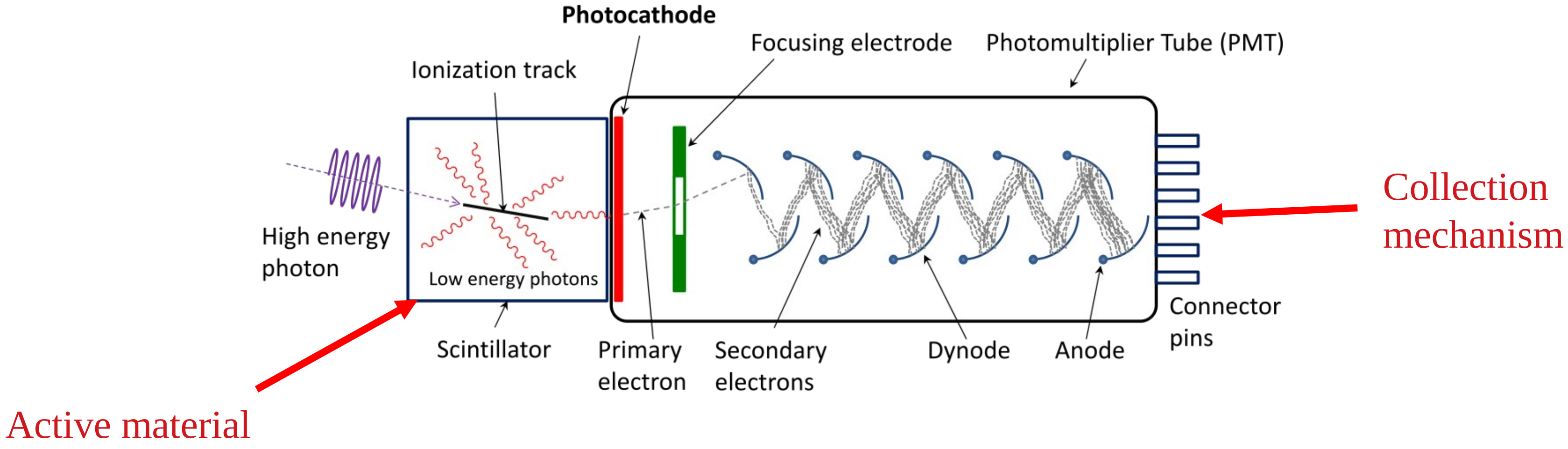
Chapter 2. Particle detectors



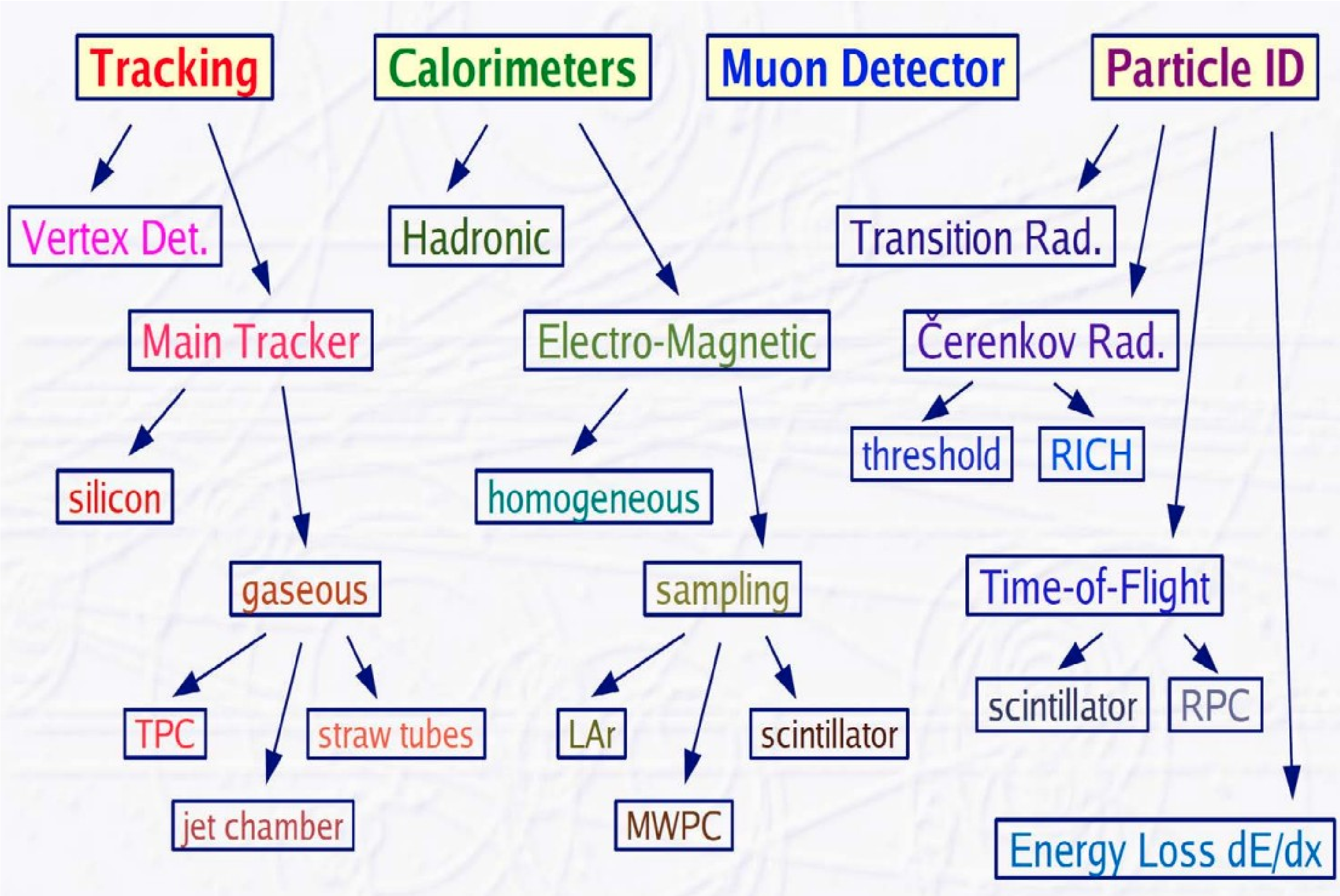
Introduction

- Particle Physics experiments and applications require some kind of device able to:
  - Identify when/if a particle is passing through it
  - Measure one or several properties of the particle (energy, momentum, charge, spin, etc.)
  - Possibly identify the type of particle
- Devices with these functionalities are called **“Particle Detectors”**
- Most particle detectors are logically composed by two parts:
  - **Active material:** volume where the particle interacts with the detector producing “signal”
  - **Collection mechanism:** system able to detect and possibly reconstruct the signal



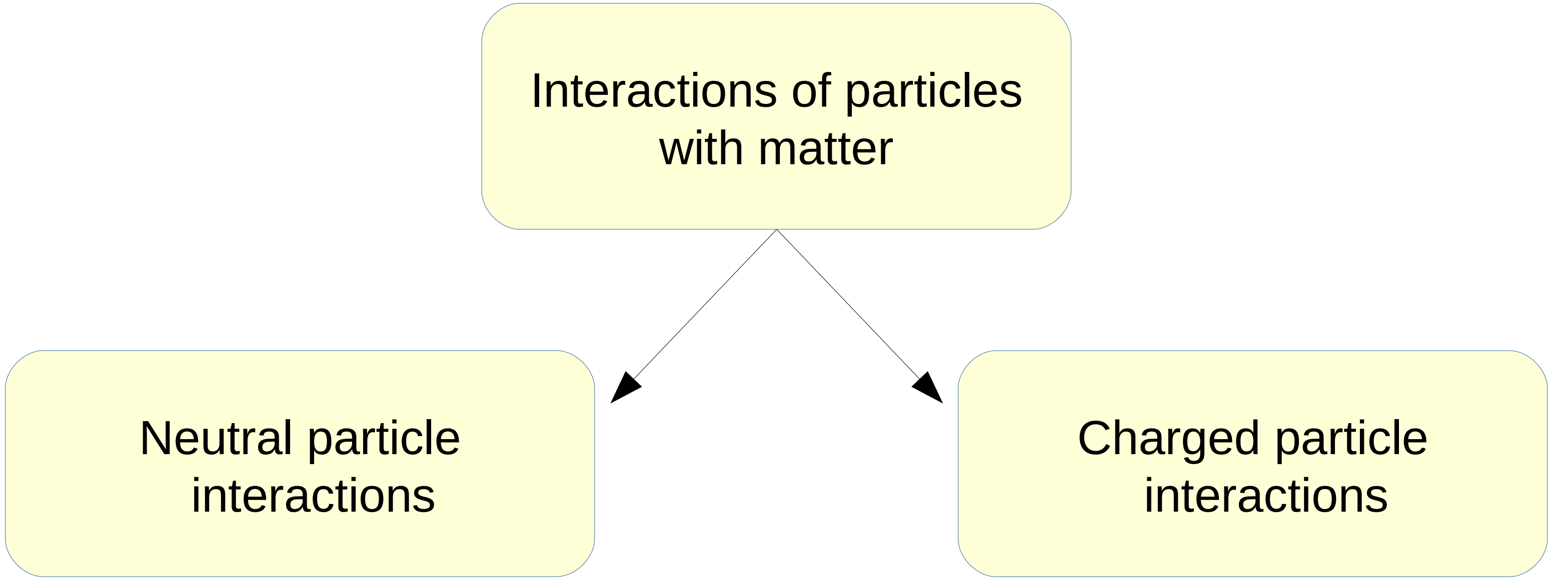
The detector zoo

- There is a large variety of detectors according to the type of particle and the technology used



Active material: interactions with matter

- Particles interact with the electrons and/or nuclei of the medium they cross
- This interaction can be electromagnetic, weak or strong depending on the particle
- The effects of this interaction can be used to detect the particles
- To understand how detectors work we need to understand how particles interact with matter
- Detectors should have an active material in which this interaction takes place



Neutral particle interactions

- Neutral particles such as photons, neutrons, K^0, and others suffer different interactions

Photons

Photoelectric effect

Comptom effect

Pair production

Moderate/Low energy neutrons

Scattering

Absorption

Fission

High Energy neutral hadrons (n, K^0)

Nuclear interactions

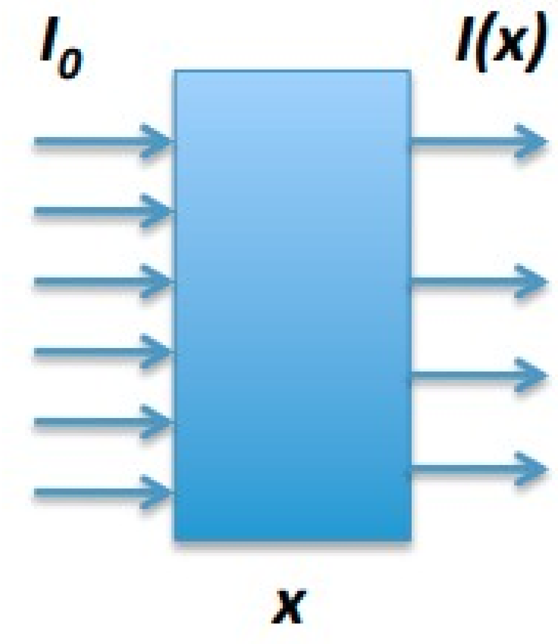
Neutrinos

Weak interactions

Not covered in this lecture

Photon interactions

- Since photons do not have charge they are always indirectly detected:
  - In their interactions they produce electrons/positrons that interact with matter
- Photons may be absorbed (photoelectric effect or e^+e^- creation) or scattered (Compton effect)
- An attenuation law is introduced based on the fact that the interaction probability is constant



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

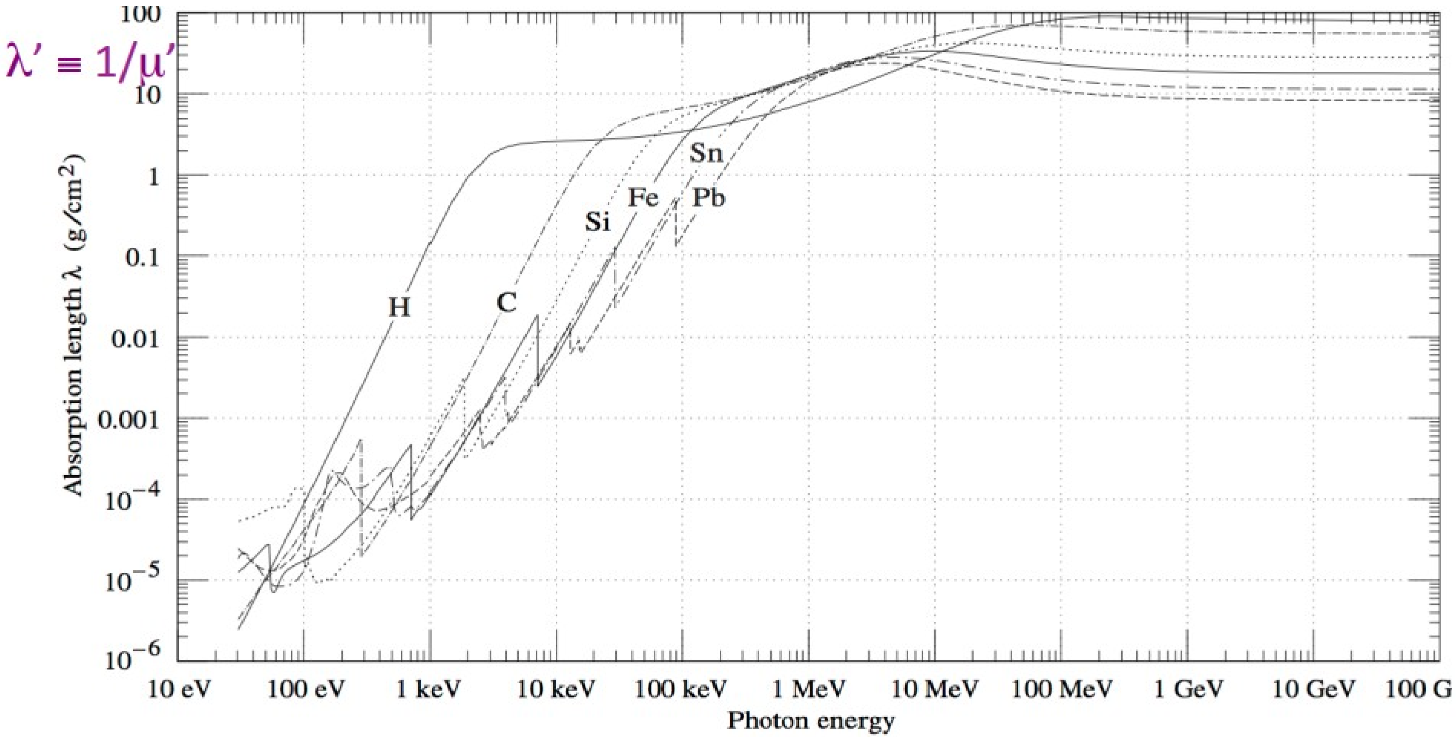
μ absorption coefficient
N atoms/m^3
A masse molaire
N_A nombre Avogadro
ρ density
σ Photon cross section
λ Mean free path or absorption lenght

$$\boxed{\mu = N\sigma = \frac{N_A}{A}\rho\,\sigma \equiv \frac{1}{\lambda}}$$

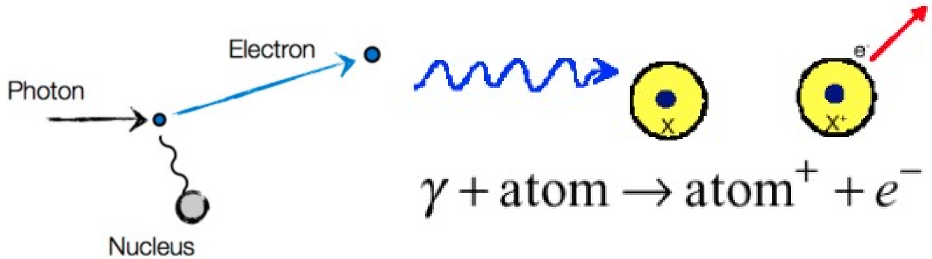
Photon absorption length

- Frequently instead of working with the distance we use the distance times density
  - This quantity is more sensitive to the real amount of matter in the crossed distance

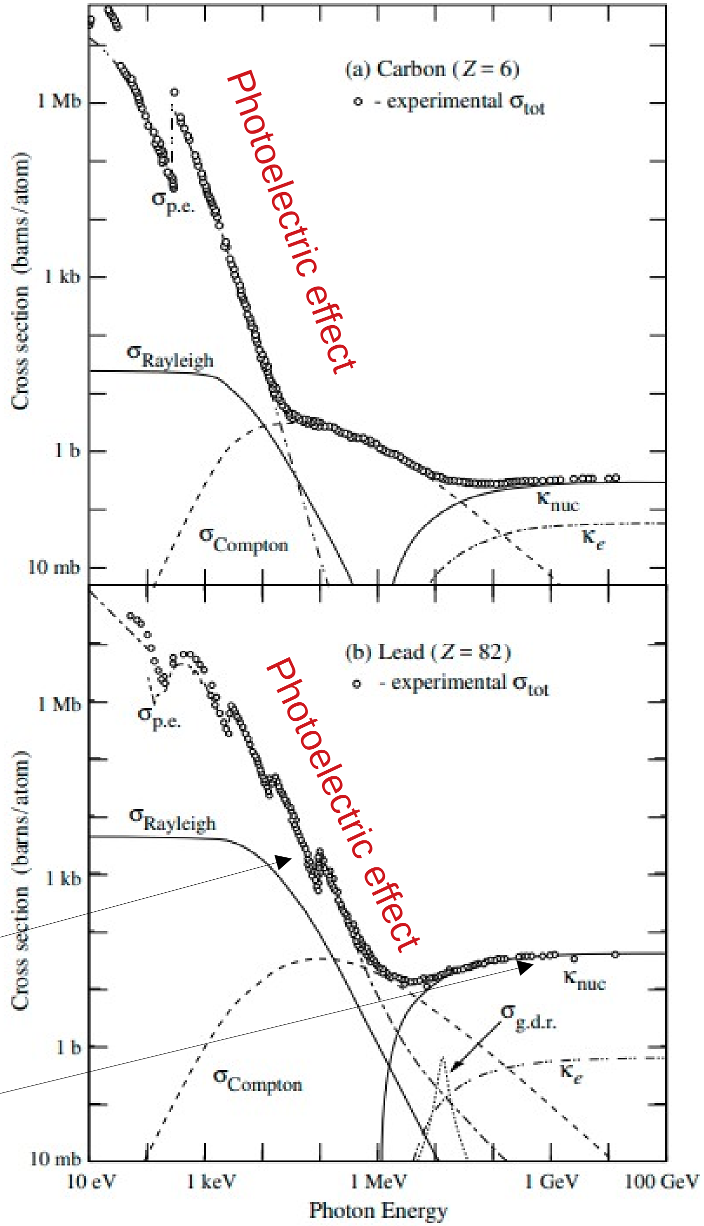
$$I(x)=I_0 e^{-\mu x} \longrightarrow \begin{array}{l} x'=x\rho \\ \mu'=\mu/\rho \\ \lambda'=1/\mu' \end{array} \longrightarrow I(x)=I_0 e^{-\mu' x'}$$



Photoelectric effect



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



- The energy of the photon is transferred to the electron
- The photon is absorbed and the electron is extracted
  - The atom gets ionized
- The final energy of the electron depends on the binding energy (the electron energy level in the atom)

$$E_e = h\nu - E_{e\,binding}$$

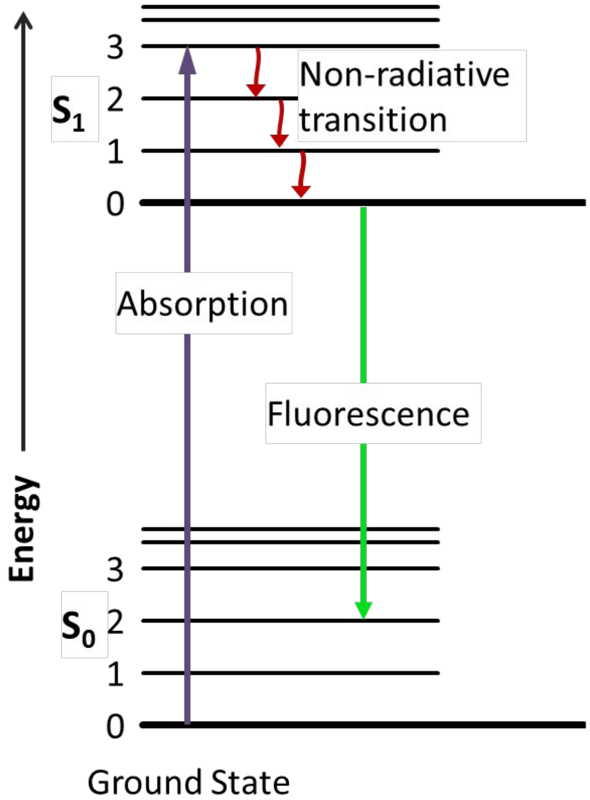
- Different trends at low and high energies

$$\sigma \sim Z^5 / E_\gamma^{3.5}$$

$$\sigma \sim Z^5 / E_\gamma$$

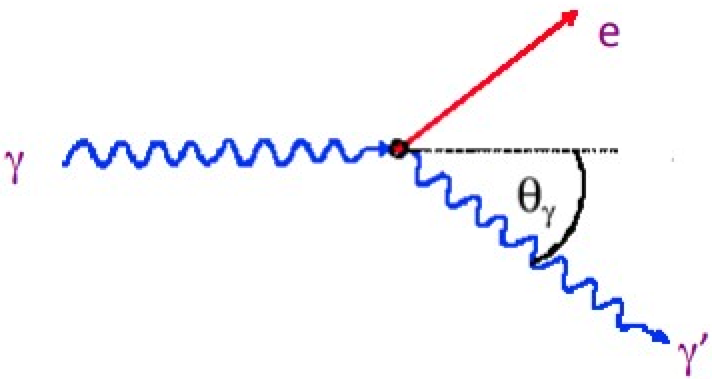
(After) Photoelectric effect: fluorescence

- After the emission of a photoelectron the ionizedatom (molecule) is an excited state
- The ionized atom (molecule) returns to the ground state emiting photons
- This is an important effect in a kind of active materials called: scintillators



Compton scattering

- Scattering of light on free electrons (if $E_{photon} >> E_{binding}$ a binded electron is considered free)



$$\boxed{E_k^e = E_\gamma - E_{\gamma'} = E_\gamma \frac{(1-\cos\theta)\,(E_\gamma/m_e c^2)}{1+(E_\gamma/m_e c^2)\,(1-\cos\theta_\gamma)}}$$

$$\boxed{E_{\gamma'} = \frac{E_\gamma}{1+(E_\gamma/m_e c^2)\,(1-\cos\theta_\gamma)}}$$

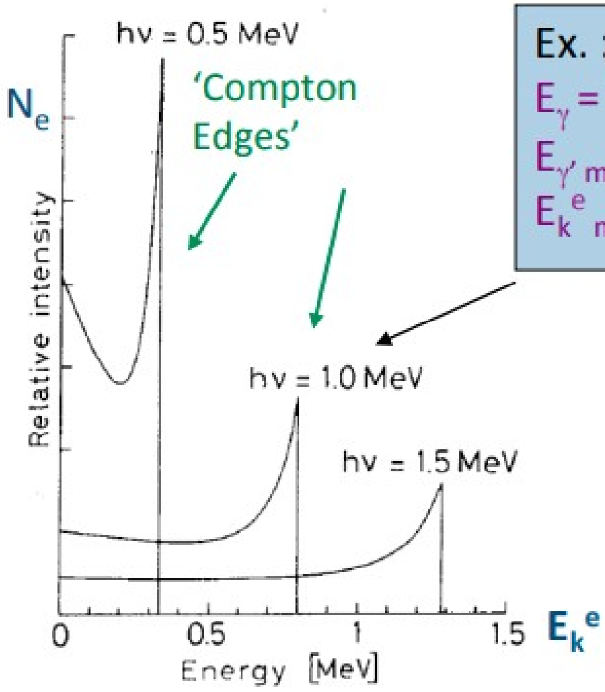
- When the angle is 0 the initial photon gives all its energy to the outgoing photon
- When the angle is backwards the outgoing electron has maximum energy
  - And the outgoing photon minimum energy but it cannot get completely absorbed

Compton edges and cross section

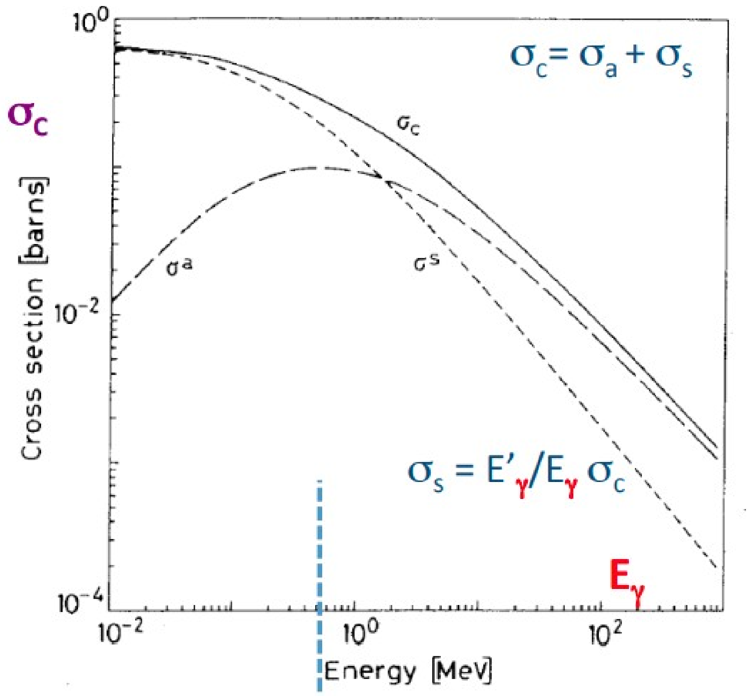
- The photon can never give all its energy to the electron producing the so called "edges"
- The cross section is given by the Klein-Nishina formula

$$\epsilon = \frac{E_\gamma}{m_e}$$

$$\sigma_c^e = 2\pi r_e^2 \left(\left(\frac{1+\epsilon}{\epsilon^2} \right) \left\{ \frac{2(1+\epsilon)}{1+2\epsilon} - \frac{1}{\epsilon} \ln(1+2\epsilon) \right\} + \frac{1}{2\epsilon} \ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2} \right) \quad (\textit{per electron})$$

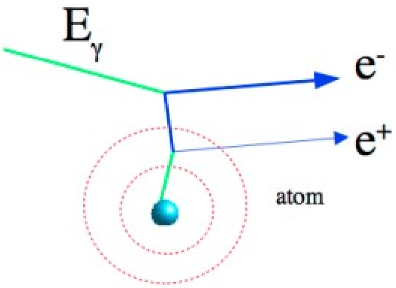


Ex. :
$E_\gamma = h\,\nu = 1$ MeV
$E_{\gamma',\,min} = 0.2$ MeV
$E_{k\ max}^{e} = 0.8$ MeV

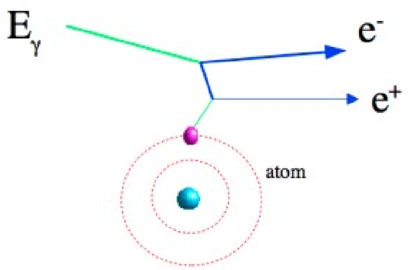


Pair production of electron-positron

- The photon interacts with the field of a nucleus or electron and makes a pair e^+e^-
  - This process cannot take place in the vacuum because of energy-momentum conservation



Pair production in the field of a nucleus



Pair production in the field of an electron

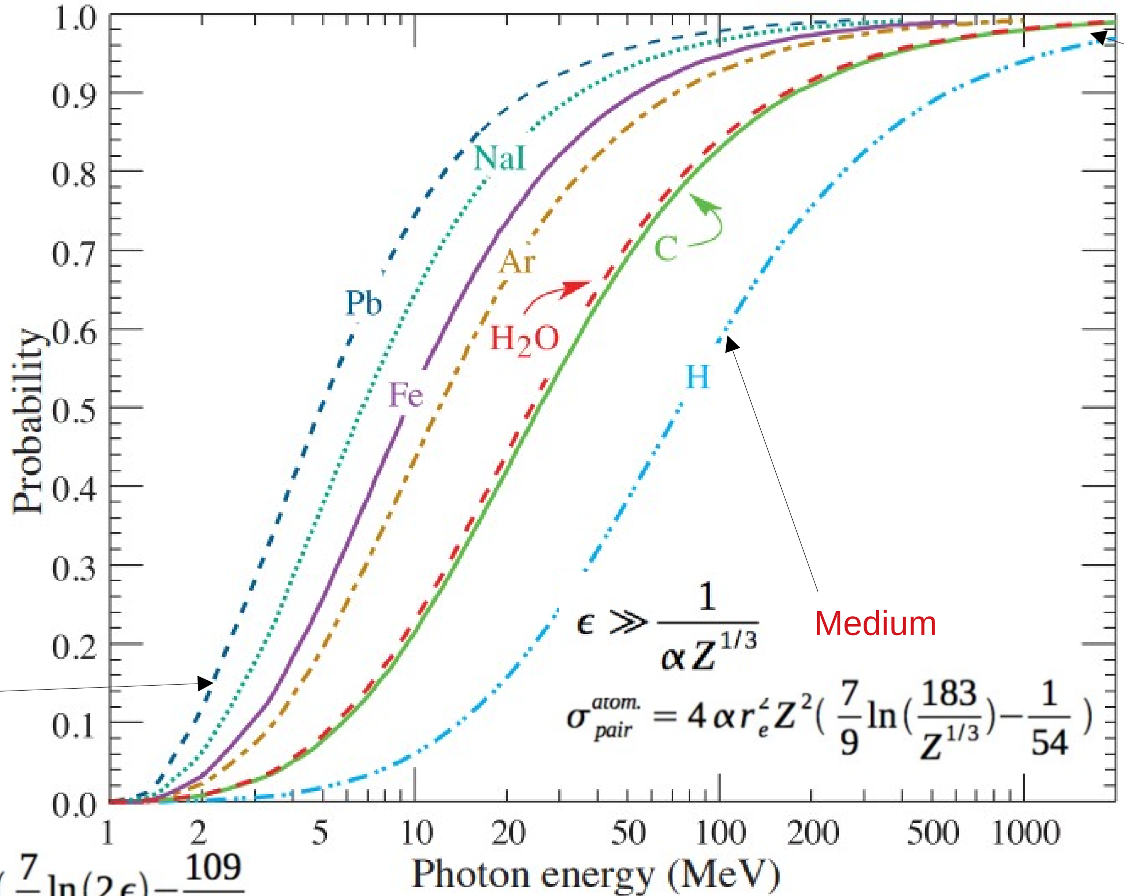
- It is also frequently known as “photon conversion”
- This effect is a “threshold effect”: the photon energy has to be enough to generate 2 electrons

$$E_\gamma > 2 m_e c^2 \left(1 + m_e / m_x\right) \qquad m_x = \left\{ \begin{matrix} m_N \\ m_e \end{matrix} \right\}$$

Pair production of electron-positron

- The cross section of pair production rises one the threshold has been reached
- Three different regions: “low”, “medium” and “high” (saturation) energy regimes

$$\epsilon = \frac{E_\gamma}{m_e}$$



Saturation

$$\varepsilon \to \infty$$

$$\sigma_{pair}^{atom.} \simeq \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

Medium

$$\epsilon \gg \frac{1}{\alpha Z^{1/3}}$$

$$\sigma_{pair}^{atom.} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln\left(\frac{183}{Z^{1/3}}\right) - \frac{1}{54}\right)$$

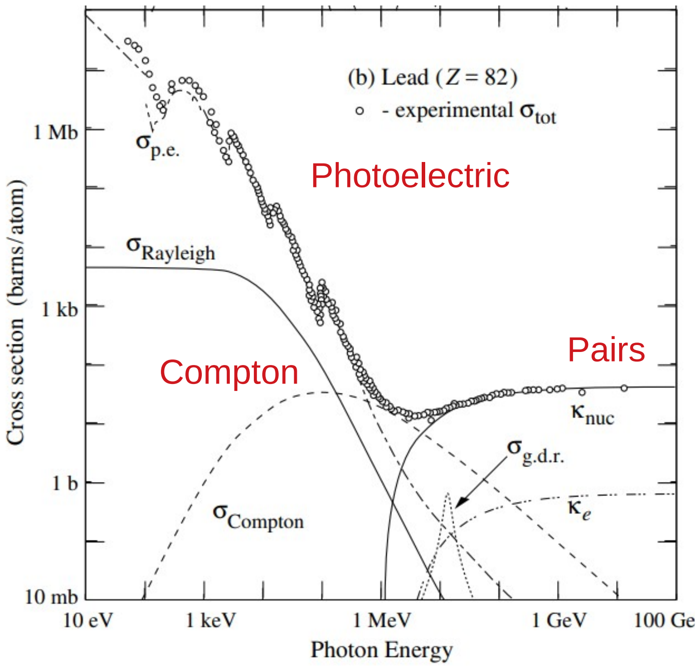
Low

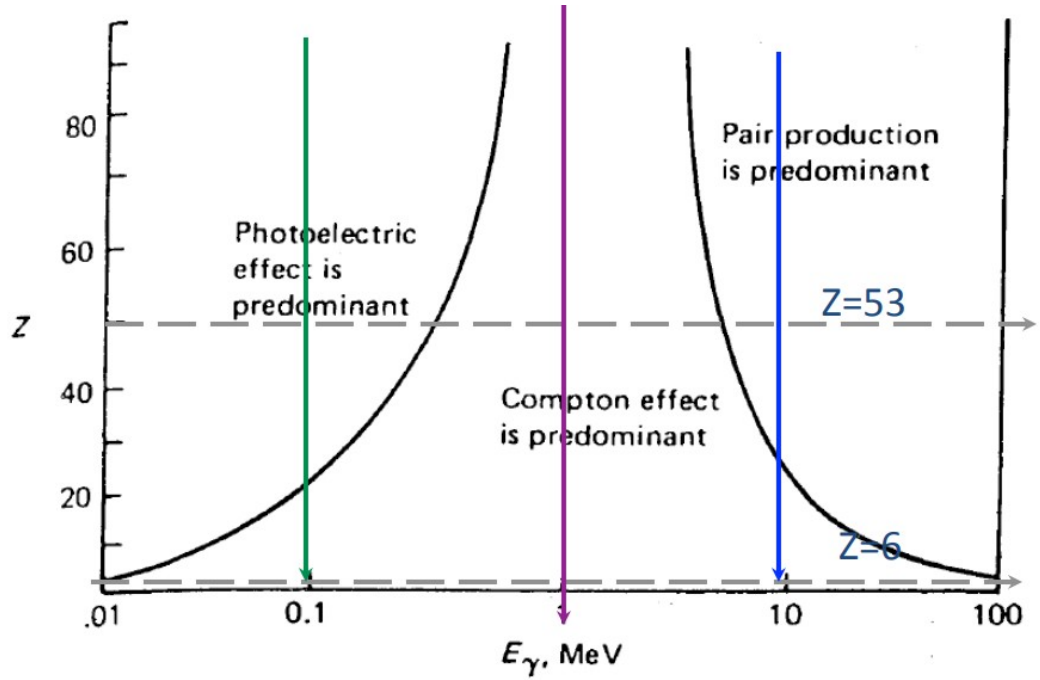
$$1 \ll \epsilon < \frac{1}{\alpha Z^{1/3}}$$

$$\sigma_{pair}^{atom.} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9}\ln(2\epsilon) - \frac{109}{54}\right)$$

Photon total cross section

- Photoelectric effect dominates at low, Compton at medium and pair production at high E
- Compton dominates for low Z materials (photoelectric and pair production increase with Z)
- Other processes not treated here: Raylaigh scattering, photo nuclear interactions





Hadron collisions and interaction lenghts

- The total cross section for very high energy hadrons is expressed as: $\sigma_T = \sigma_{elastic} + \sigma_{inelastic}$
- The inelastic part of the total cross-section is susceptible to induce hadron showers
- Two mean lenghts are introduced to deal with this kind of interactions
  - Nuclear collision length: $\lambda_T = \frac{A}{N_A \sigma_T} \text{g cm}^{-2}$
    - Mean free path of a particle before undergoing a nuclear interaction
  - Nuclear interaction length: $\lambda_I = \frac{A}{N_A \sigma_{inelastic}} \text{g cm}^{-2}$
    - Mean free path of a particle before undergoing an inelastic nuclear interacion

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Abridged from `pdg.lbl.gov/AtomicNuclearProperties` by D. E. Groom (2007). Quantities in parentheses are for NTP (20° C and 1 atm), and square brackets indicate quantities evaluated at STP. Boiling points are at 1 atm. Refractive indices n are evaluated at the sodium D line blend (589.2 nm); values $\gg$1 in brackets are for $(n-1) \times 10^6$ (gases).

Material	Z	A	$\langle Z/A \rangle$	Nucl.coll. length λ_T $\{\text{g cm}^{-2}\}$	Nucl.inter. length λ_I $\{\text{g cm}^{-2}\}$	Rad.len. X_0 $\{\text{g cm}^{-2}\}$	$dE/dx\|_{\text{min}}$ $\{\text{MeV g}^{-1}\text{cm}^2\}$	Density $\{\text{g cm}^{-3}\}$ $(\{\text{g}\ell^{-1}\})$	Melting point (K)	Boiling point (K)	Refract. index (@ Na D)
H_2	1	1.00794(7)	0.99212	42.8	52.0	63.04	(4.103)	0.071(0.084)	13.81	20.28	1.11[132.]
D_2	1	2.01410177803(8)	0.49650	51.3	71.8	125.97	(2.053)	0.169(0.168)	18.7	23.65	1.11[138.]
He	2	4.002602(2)	0.49967	51.8	71.0	94.32	(1.937)	0.125(0.166)		4.220	1.02[35.0]
Li	3	6.941(2)	0.43221	52.2	71.3	82.78	1.639	0.534	453.6	1615.	
Be	4	9.012182(3)	0.44384	55.3	77.8	65.19	1.595	1.848	1560.	2744.	
C diamond	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.725	3.520			2.42
C graphite	6	12.0107(8)	0.49955	59.2	85.8	42.70	1.742	2.210			

Neutron interactions

- Neutrons interact via the "strong interaction" with nuclei (short range force ~ 10^{-13} cm)
- Classification of neutrons:
  - Cold or ultracold neutrons $E_n < 0.025$ eV
  - Thermal or slow neutrons $E_n \sim 0.025$ eV
  - Intermediate neutrons $E_n \sim 0.025$ eV – 0.1 MeV
  - Fast neutrons $E_n \sim 0.1$ MeV – 10-20 MeV
  - High energy neutrons $E_n > 20$ MeV

<u>Low-moderate energy neutrons</u>

Scattering

Absorption

Fission

<u>High energy neutrons</u>

Hadron shower production

Low-intermediate energy Neutron interactions

- Scattering with nuclei (important for moderation): $n + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X^{(*)} + n$
  - The neutron changes energy and the nucleus gets in an excited state
- Absorption and nuclear reactions (the neutron is absorbed and a nuclear reaction takes place)
  - Low A-Z transitions (typically emission of a proton, alpha particle, or neutrons)

$$n + {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + p$$

$$n + {}^{A}_{Z}X \rightarrow {}^{A-3}_{Z-2}Y + {}^{4}_{2}H_{e}$$

$$n + {}^{A}_{Z}X \rightarrow {}^{A-1}_{Z}X + 2n$$

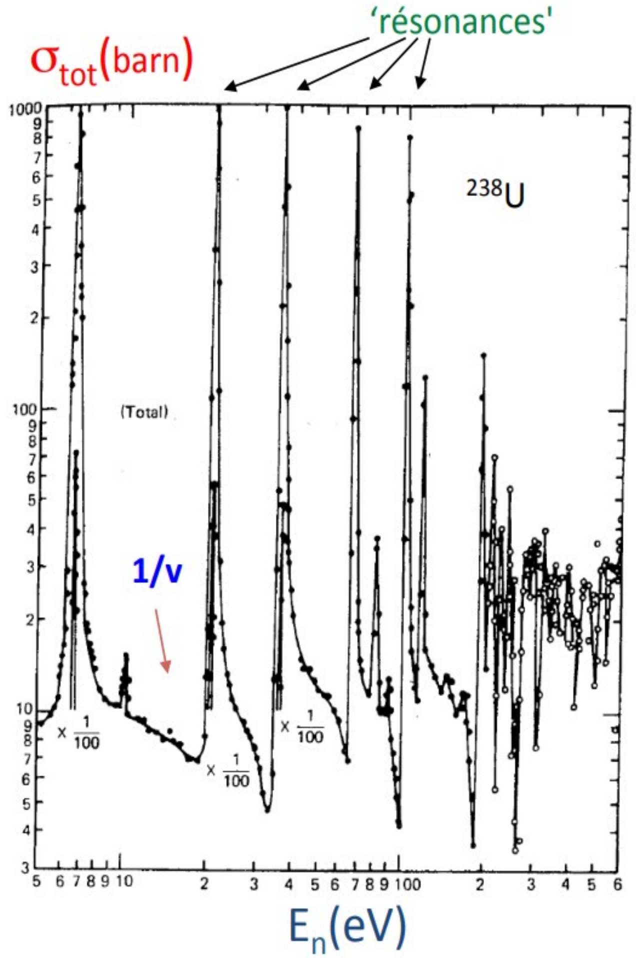
$$n + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X + \gamma$$

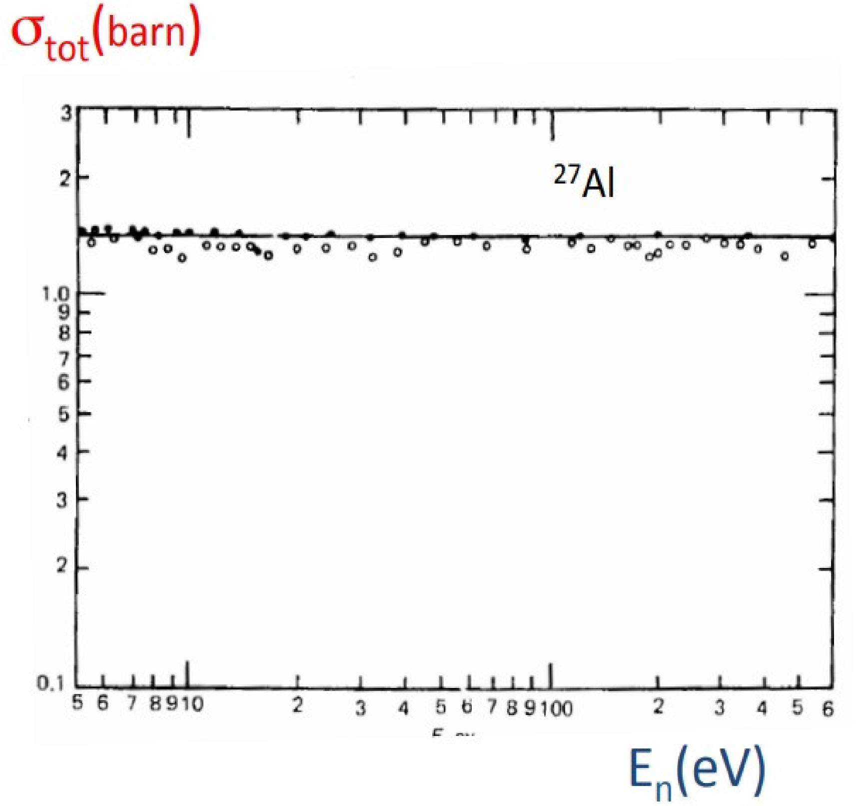
- Fission process: the nucleus is splitted in two and more neutrons are produced
  - High A-Z transitions
  - Importan for chain reactions in nuclear reactors

$$n + {}^{A}_{Z}X \rightarrow {}^{A1}_{Z2}Y + {}^{A2}_{Z2}Y + n + n + \ldots$$

Low-intermediate energy Neutron cross sections

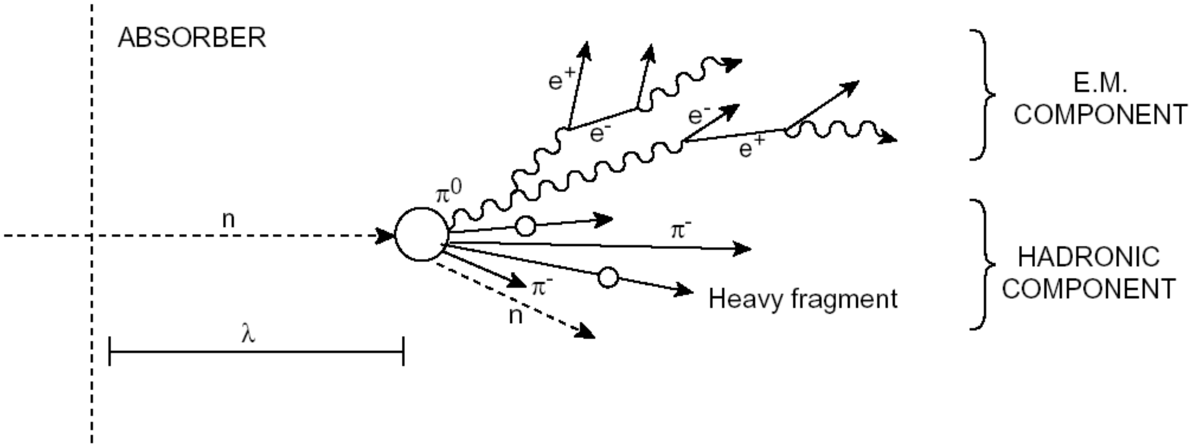
- The cross-section goes like ~ $1/v_n$ with v_n the velocity of the neutron
- On top of this effect there are the absorption resonances characteristic of every nucleus

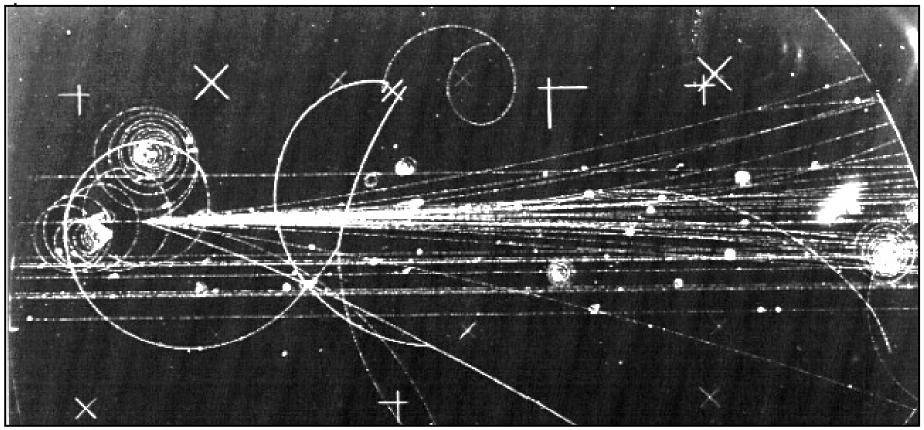




Hadron showers

- The incident hadron produces a chain of reactions through inelastic interactions
  - Producing pions, low energy photons, low energy neutrons, neutrinos, photons
- Produces a shower of particles with two different components: electromagnetic and hadronic





Charged particle interactions

- Charged particles suffer a wide variety of different interactions

Ionization

Bremsstrahlung

Multiple scattering

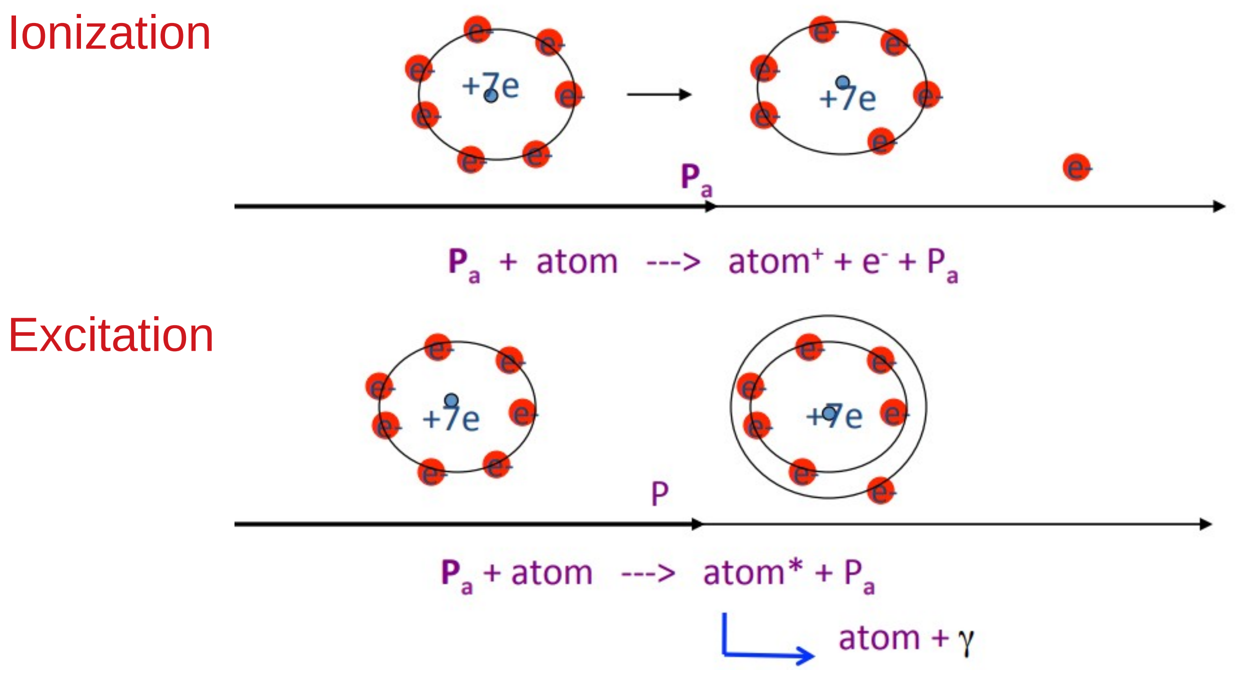
Cherenkov

Transition Radiation

Nuclear Interactions

Inelastic collisions with atom electrons (Ionization)

- The charged particle interacts, giving energy, with the electron of an atom
  - This process is dominant for heavy charged particles $M_{pa} >> m_e$



- Inelastic collisions on the nucleus are much less frequent (because the mass is much higher)
- The particle loses a bit of energy and its direction remains mostly unchanged

Inelastic collisions with atom electrons (Ionization)

- The avarage energy loss of a particle due to ionization is given by the Bethe & Bloch Formula
- This formula is valid for particles with a mass much higher than the electrons $m_p >> m_e$

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{\text{max}}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
m_e: electron mass
N_a: Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}
I: mean excitation potential
Z: atomic number of absorbing material
A: atomic weight of absorbing material
ρ: density of absorbing material
z: charge of incident particle in units of e
$\beta =$ v/c of the incident particle
$\gamma =$ $1/\sqrt{1-\beta^2}$
δ: density correction
C: shell correction
W_{max}: maximum energy transfer in a single collision.

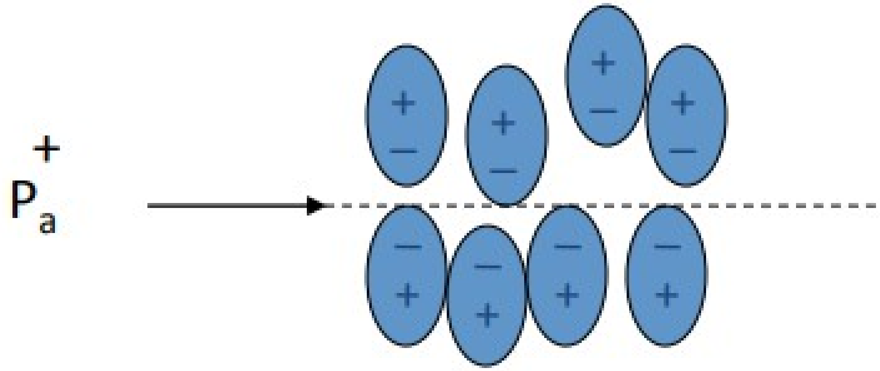
- The maximum energy transfer takes place in head-on or knock-on collisions

$$W_{max} = E_a^{max} - m_e = \frac{2 m_e \beta^2 \gamma^2}{\left(E_{CM}/M\right)^2}$$

Shell and Density effect corrections

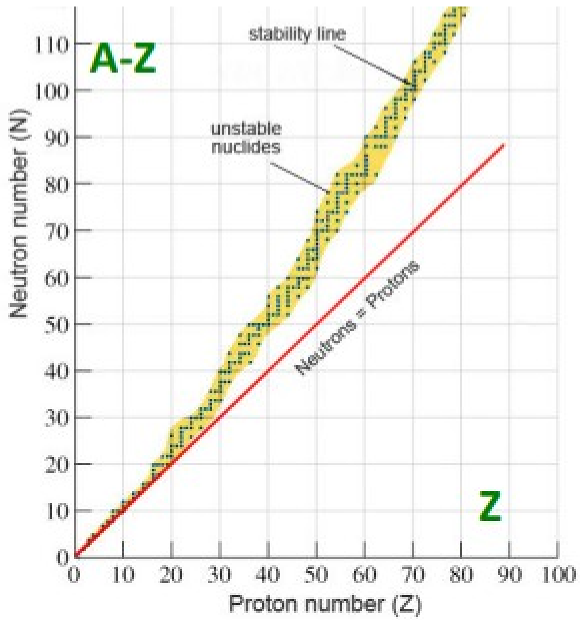
- The C term accounts for the fact that the electron is not at rest in the atom
  - It is a small correction only relevant at low energies
  - If the binding energy of the electron is taken into account the energy loss is reduced
- The "δ" term or "density effect" → accounts for the polarization induced by the particle
  - The atoms get polarized due to the charge of the particle
  - The energy loss is reduced because of the shielding of the electric field
  - It depends on the particle speed and on the matter densitiy
  - This process is relevant at high energy

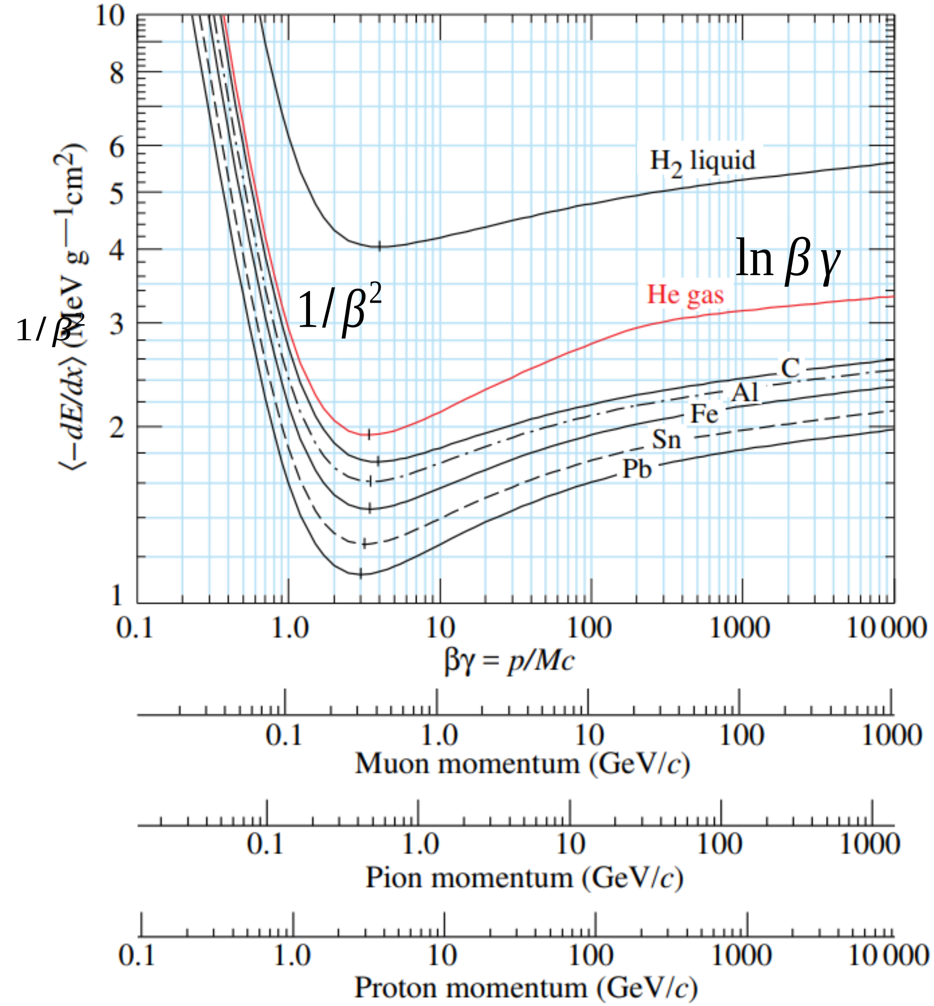
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 \boxed{- \delta - 2\frac{C}{Z}} \right]$$



Stopping power or mean specific energy loss

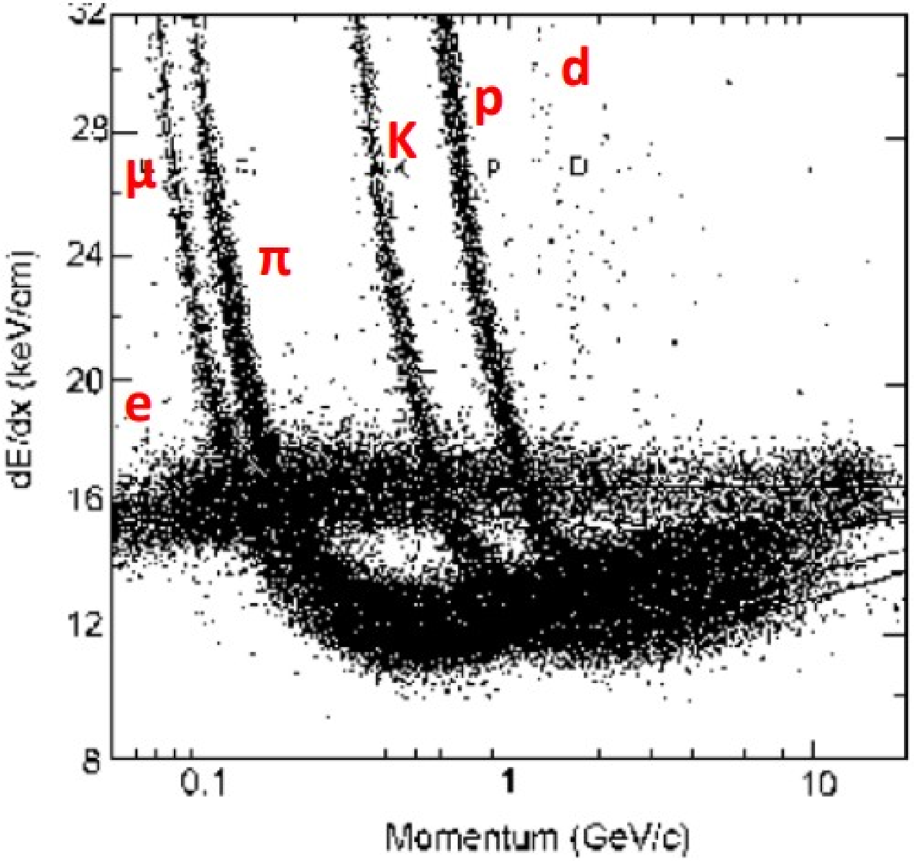
- The energy loss is usually given in the form of the stopping power $-dE/(\rho\, dx)$
- The dependency on the material is almost removed since Z/A ~ 0.5
- At low energy the term $1/\beta^2$ dominates
- At high energy → logarithmic term
- There is a minimum of ionization
  - MIP → Minimum Ionizaing Particle





Use of dE/dx for particle identification

- The energy loss can be used to identify particles if the momentum is measured independently
- Indeed with the momentum known the Bethe Bloch formula can be used to measure β
- With the momentum and β known the mass of the particle can be extracted

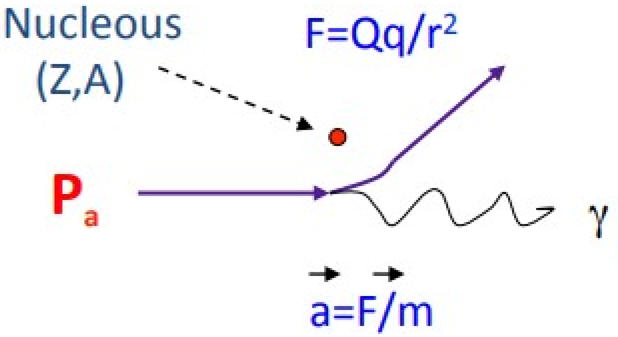


Plot from
PEP4-9
Time Projection Chamber
@SLAC (late '70)

Bremsstrahlung. Mean radiative energy loss

- An accelerated or decelerated charged particle emits electromagnetic radiation
- This effect takes place when the particle is accelerated in the field of a nucleous
- It is particularly relevant for electrons and positrons due to their small mass

$$\boxed{-\left(\frac{dE}{dx}\right)_{\text{brem}} = N \int_{\sim 0}^{\nu_0 = E_o/h} h\nu \frac{d\sigma}{d\nu} d\nu = N E_0 \phi(Z^2)}$$



For electrons

If $E_0 >> m_e c^2$ et $E_0 << 137\, m_e c^2 / Z^{1/3}$

$$\phi(Z^2) = 4\alpha\, Z^2 r_e^2 \ln(2E_0/m_e c^2 - 1/3 - f(Z))$$

If $E_0 >> 137\, m_e c^2 / Z^{1/3}$

$$\phi(Z^2) = 4\alpha\, Z^2 r_e^2 \ln(183\, Z^{-1/3} - 1/18 - f(Z))$$

For other particles

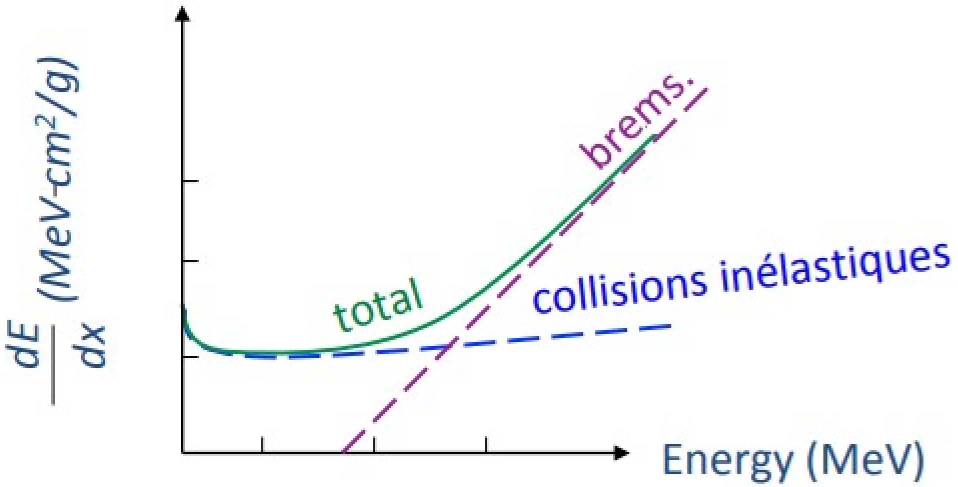
$$\frac{dE}{dx}_{\text{brem}}(z,m) = \left(\frac{m_e}{m}\right)^2 z^2 \, \frac{dE}{dx}_{\text{brem}}(e^-)$$

N = atoms/cm³ ($N = \rho N_A/A$)
Z = atomic number

E_0 = Initial energy of particle P_a
$\nu_0 = E_0/h$
$h\nu$ = energy of emitted γ
$\frac{d\sigma}{d\nu}$ = Differential cross section of the bremsstralung process

Comparison of Bremsstrahlung vs. ionization

- The average energy loss due to ionization increases with the log of energy and linear with Z
- The average energy loss due to Brem increases linearly with energy and linear with Z^2
- The energy in which the two stopping powers equal each other is called the critical energy



For $e^{\pm}$ in :

Pb	Ec = 9.5 MeV
Cu	Ec = 24.8 MeV
Fe	Ec = 27.4 MeV
Al	Ec = 51 Mev

For liquid and solids: $E_c \sim$ 610 MeV/(Z+1.24)

For gas $E_c \sim$ 710 MeV/(Z + 0.92)

- For other particles the critical energy scales according to the square of the mass ratio

$$E_c(Pa) \propto (m_{Pa}/m_e)^2 E_c(e)$$

Radiation length X_0

- For high energy particles most of the energy loss comes from Bremsstrahlung radiation
- The radiation length is defined as the length in which a particle has radiated 1/e of its energy

$$\frac{-dE}{dx} = N E_0 \Phi \qquad\qquad X_0 = \frac{1}{N\Phi}$$

- A specific radiation length is also defined to reduce the dependency with the material

$$X'_0 = X_0 \rho = \frac{\rho}{N\Phi}$$

- The specific radiation length can be estimated for pure elements approximately as:

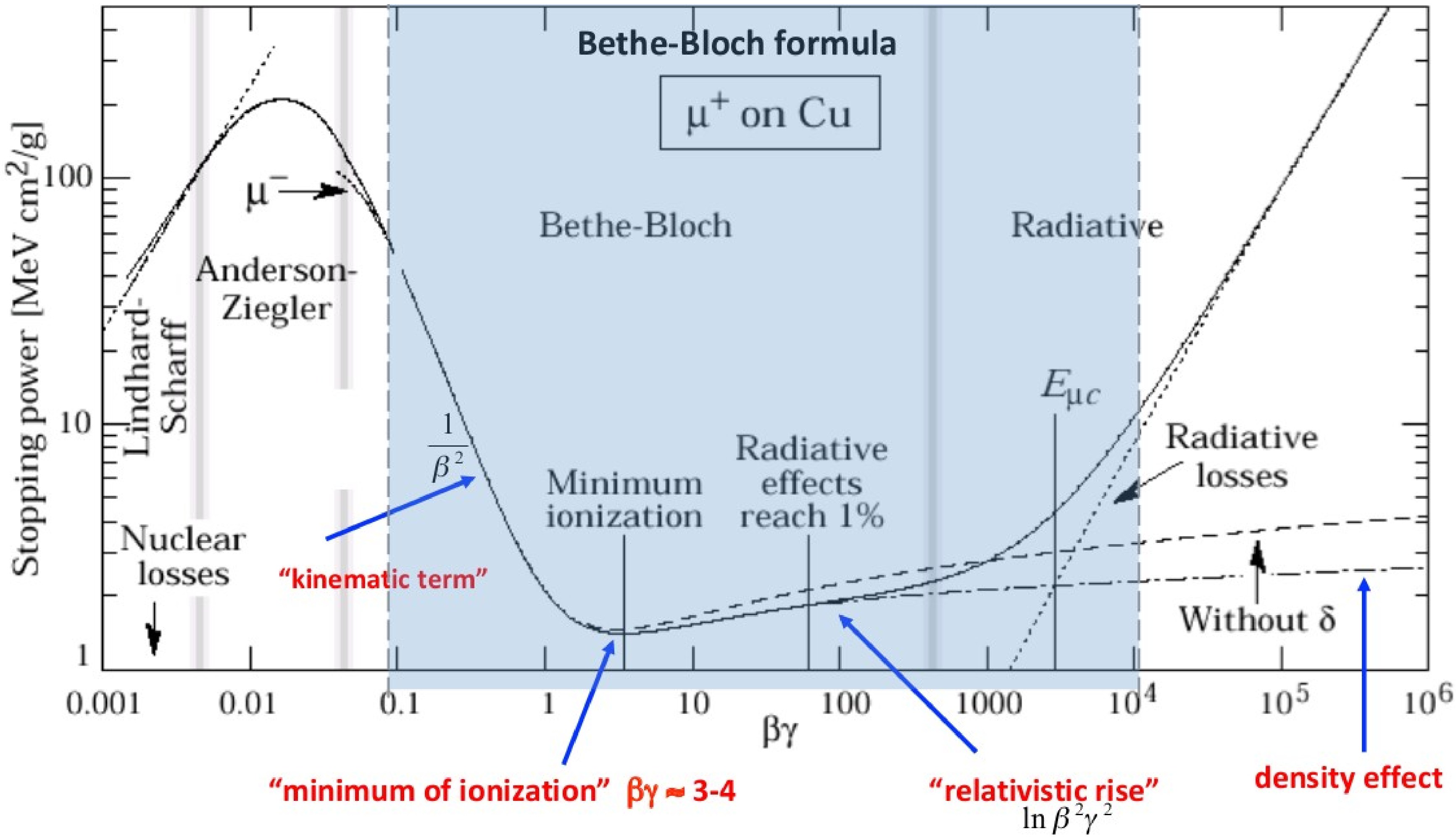
$$X_0 = \frac{716.4\, g cm^{-2} A}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)}$$

- For a material composed of many different elements:

$$\frac{1}{X_0} = \sum_i w_i \frac{1}{X_{0i}}$$

Where w_i is the fraction in mass of the element

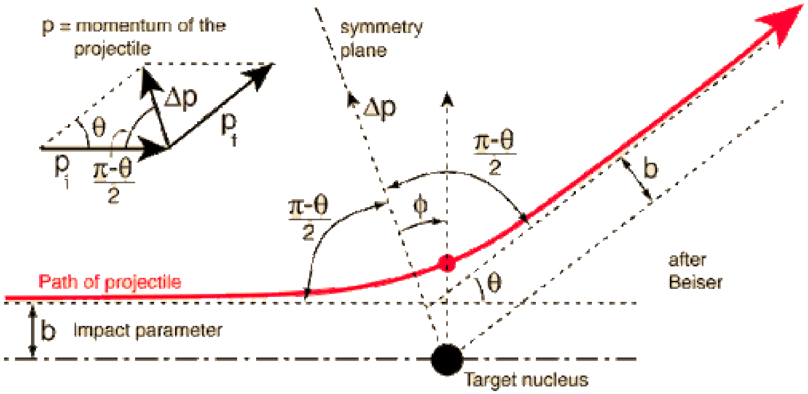
Total energy loss per unit length



Elastic scattering with nuclei

- A charged particle traversing a medium is deflected many times mainly by small angles
- Each deflection is due mainly to the Coulombian interaction of the particle and a nucleous
- Energy transferred to the nucleous is small and neglected
- A single collision is described by Rutherford's formula (ignores spin and screening effects)

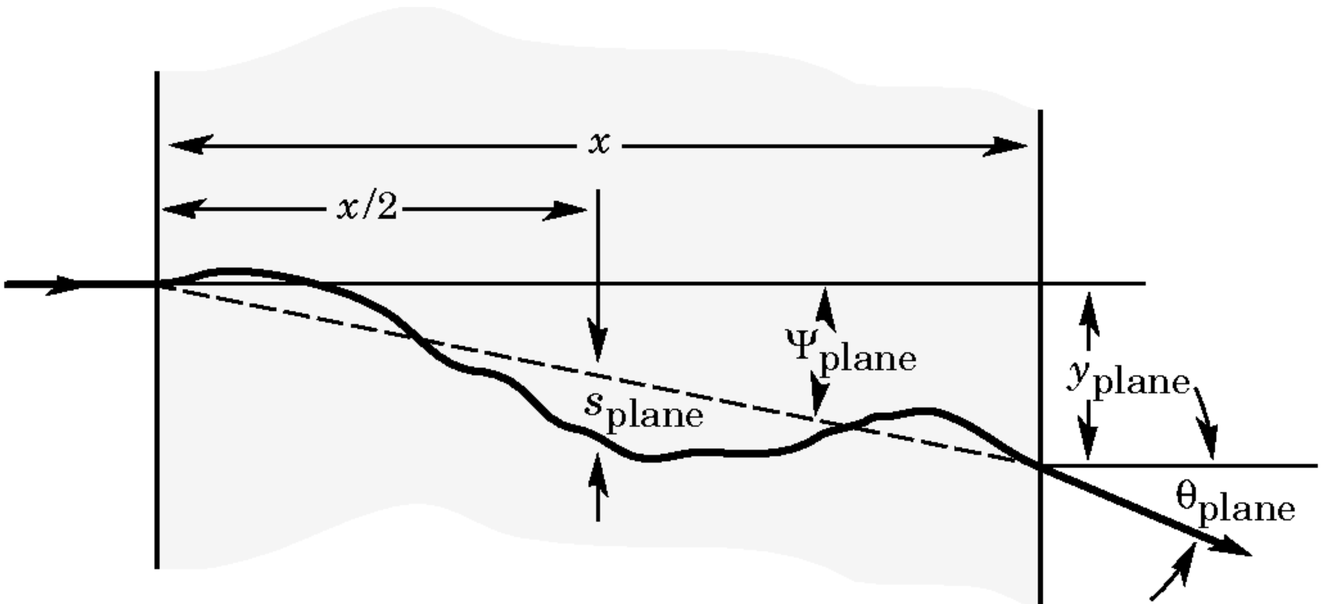
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$



- In multiple scattering typically more than 20 collisions take place during the trajectory
  - The particle follows a zig-zag trajectory of statistical nature
  - A global deflection angle given by Moliere's scattering

Multiple scattering

- The multiple scattering produces a global angular deflection and an orthogonal displacement



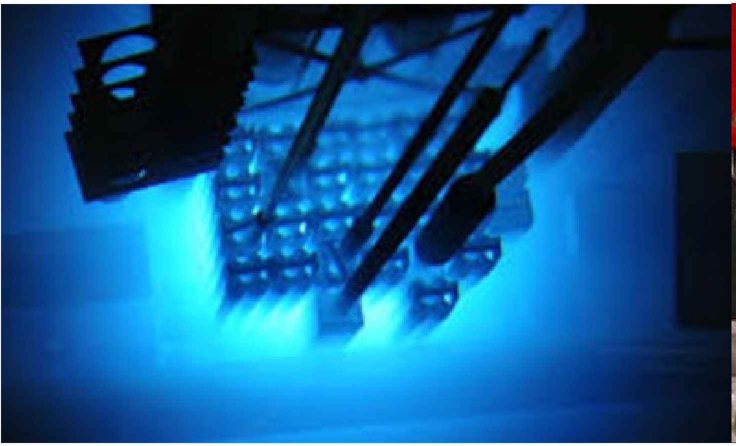
ıre 27.9: Quantities used to describe multiple Coulomb scattering.

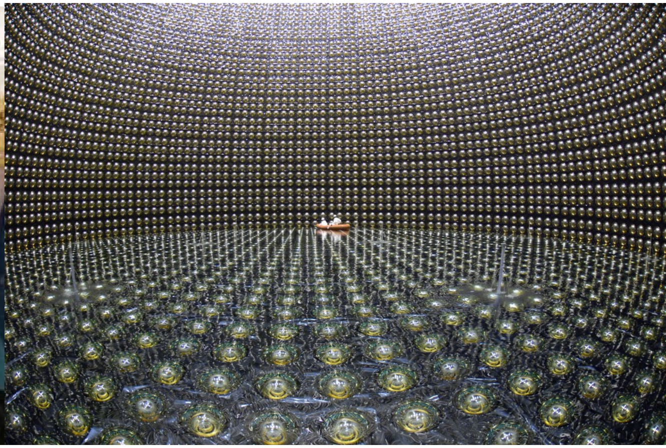
- For small deflection angles the distributions of deflections are approximately Gaussian

$$\sigma(\theta_{plane}) = \frac{13.6\ MeV}{\beta p} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \frac{t}{X_0}\right) \qquad \sigma(y_{plane}) = \frac{x\,\sigma(\theta_{plane})}{\sqrt{3}}$$

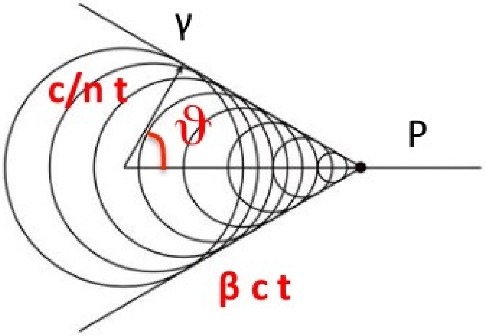
Cherenkov light emission

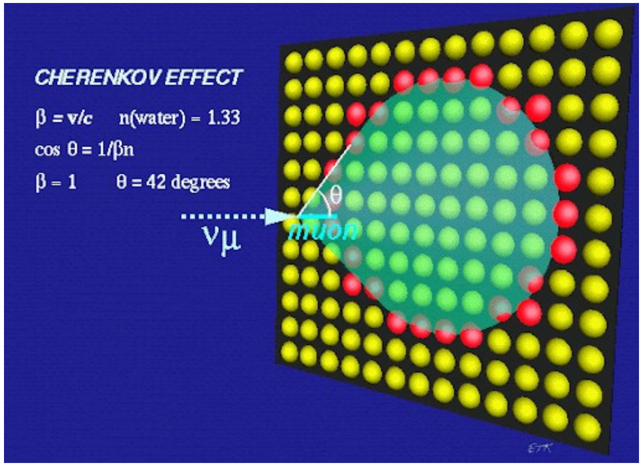
- Radiation emitted by a charged particle when it travels faster than light inside a medium





- The particle electric field polarizes the medium while going throught it
  - If v > c/n the light is emitted coherently in a cone behind the particle

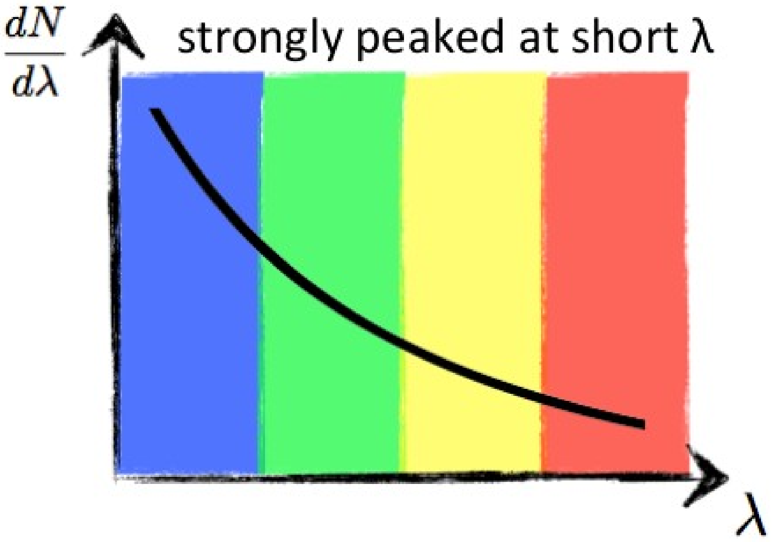




Cherenkov light emission

- The number of photons emitted per unit of length path and unit of wave length is

$$\frac{dN}{dx\,d\lambda} = 2\pi\alpha \frac{1}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) z^2$$



- The number of photons per unit path length

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\beta n > 1} \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^2}$$

- Assuming n is constant over the wavelength region detected

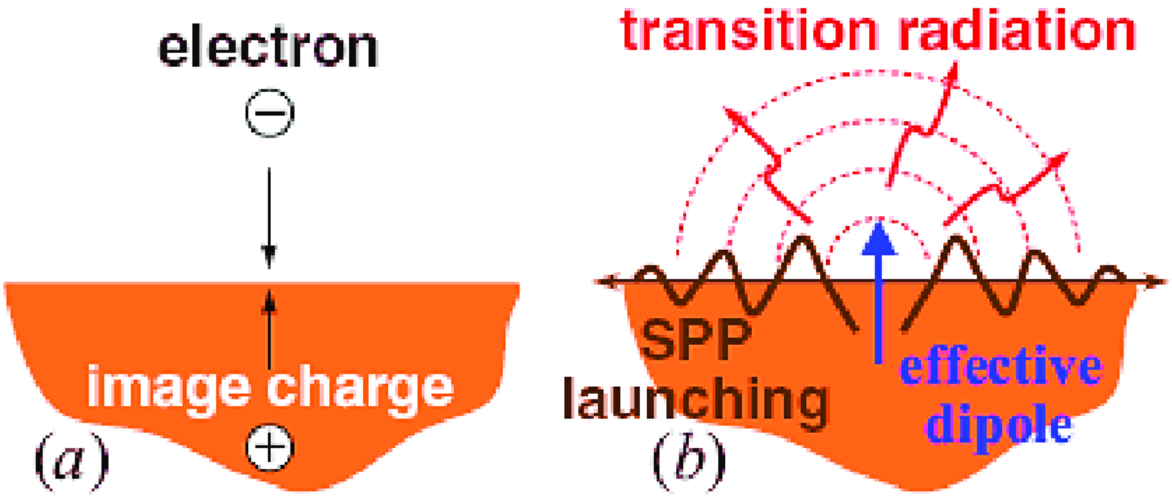
λ=350-500nm

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) z^2 \longrightarrow \frac{dN}{dx} = 390 \sin^2\theta \; photons/cm$$

- Loss of energy due to Cherenkov radiation is very small compared to ionization and much weaker than scintillation output so it's usually neglected

Transition radiation

- When a relativistic charged particle crosses a boundary between two materials with different dielectric properties, radiation is emitted, mostly in the form of X-rays
- This effect appears because the electric field generated by the particle is different at both sides



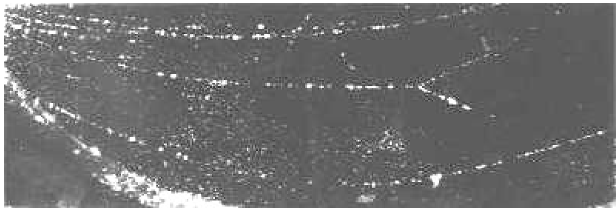
- The radiation is emitted in a cone with $\cos(\theta) = 1/\gamma$
- The probability of radiation per transition surface is low ~ 1/2 α (fine structure constant)

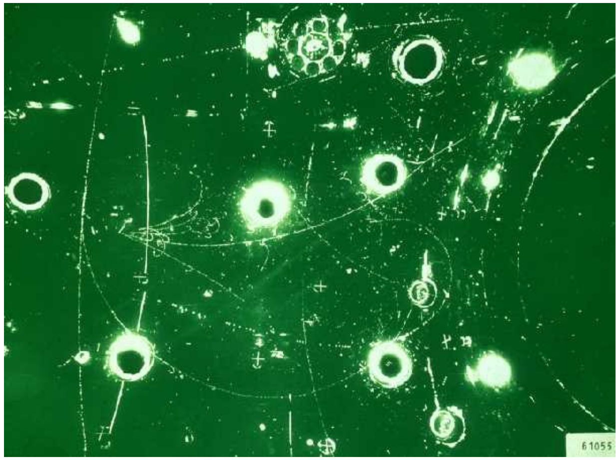
Particle detectors: the ideal detector

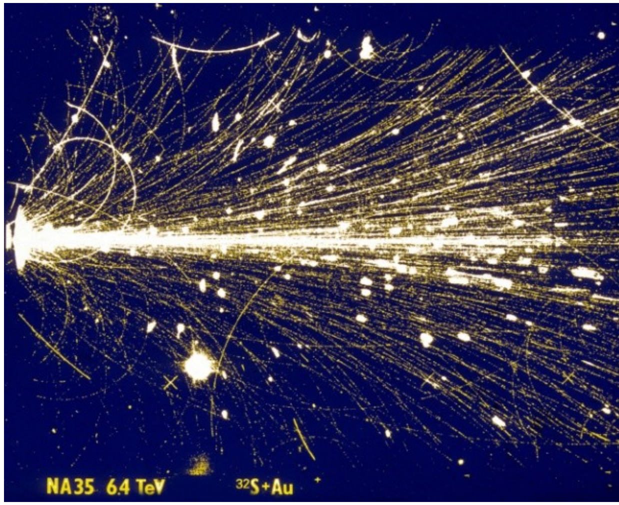
- Our ideal particle detector should have the following good properties
  - Good particle identification
  - Precise measurement of the energy and/or the momentum
  - Precise measurement of the trajectory of the particle
  - Coverage of the full solid angle (hermeticity)
- But from a practical and experimental point of view it should also:
  - Be able to take data at a high rate of particles
  - Cope with high particle densities (many particles at the same time)
  - Survive high radiation doses (so they can be installed in colliders, for instance)
  - Survive for a few years of operation (~10 años) without (little) intervention
  - Cheap

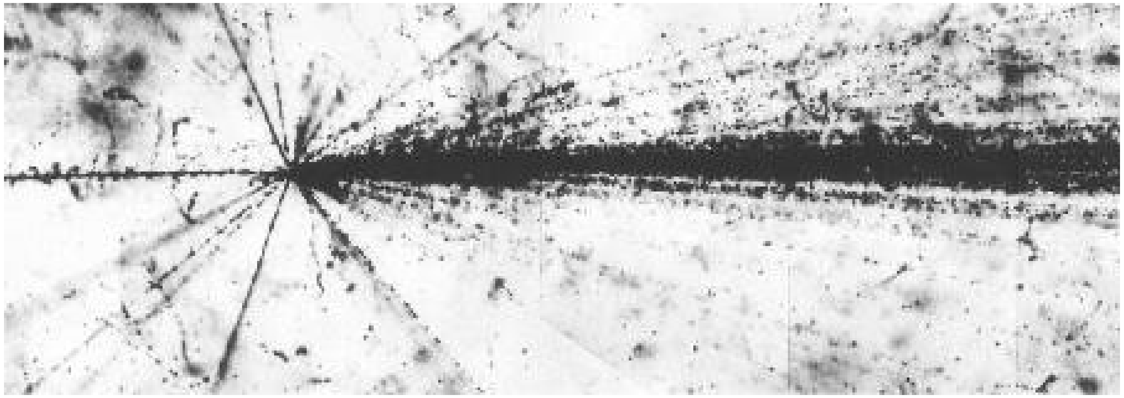
Basic detection techniques: Photographic techniques

- Charged particles ionize the atoms along their trajectory
- Ions can act as seeds for the following processes:
  - Condensation in super saturated gases (Wilson chamber)
  - Buble formation in super heated liquids
  - Electrical discharge or plasma formation
- Ions can also be made visible chemically
  - Photographic emulsion targets



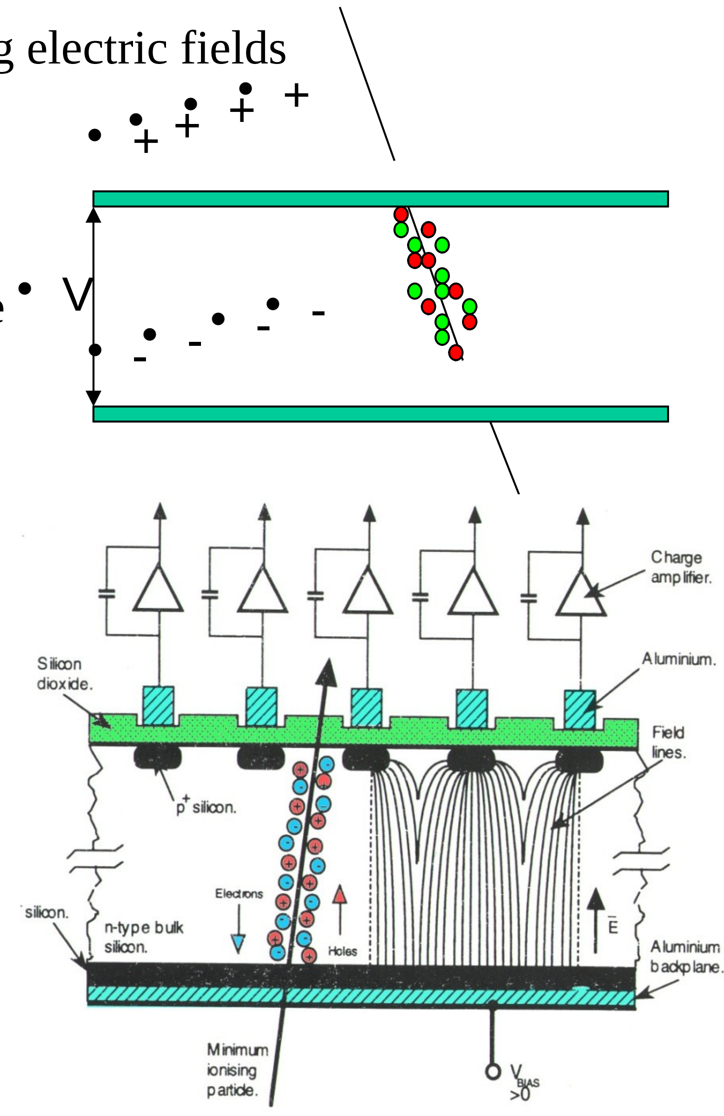






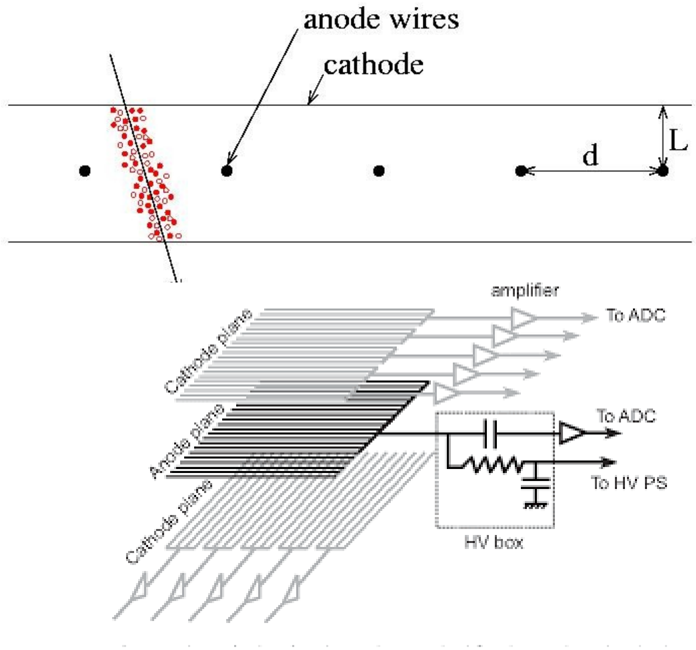
Basic detection techniques: Electrical

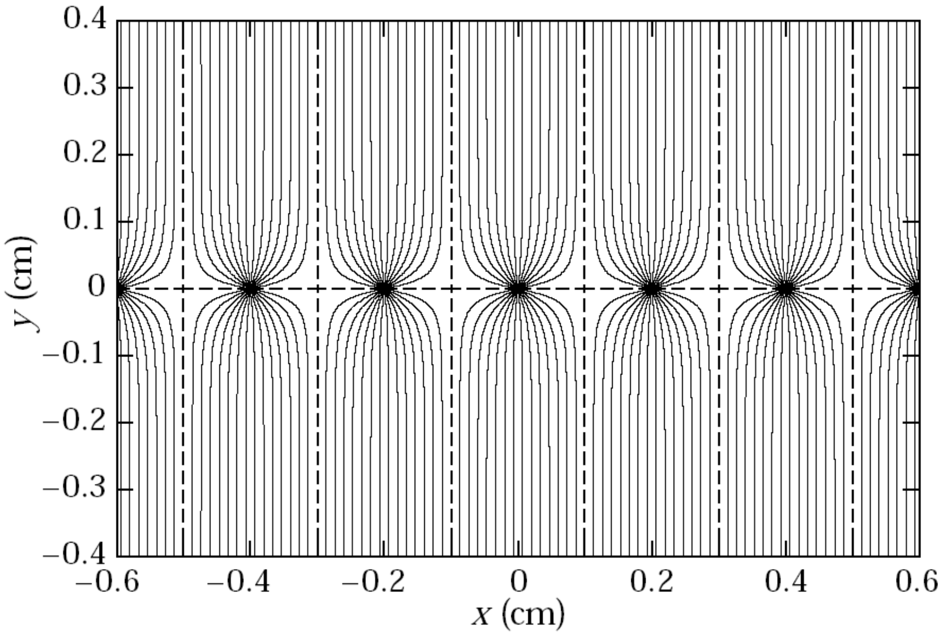
- The charge produced by the ionization can be collected electrically
  - The charge generated is conducted and collected using electric fields
- The requirements are the following:
  - The active material should be not conducting
  - There should be a mechanishm to transport the charge
- One family of these detectors are the gas/liquid based:
  - Insulting gas or liquid between anode and cathode
  - Sometimes with very low conductivity solids
  - Proportional chambers, drift tube chambers, etc
- Another family are sillicon based detectors:
  - Active material is made of semiconductor
  - Usually a reversely polarized p-n junction
  - CCDs, strip detectors, LGADs, etc



An example: Multiwire Proportional Chamber

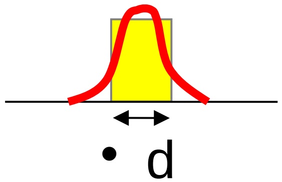
- Electrons/ions drift along field lines (ions drift to the cathode and electrons to the wire)





- These devices are sensitive to only one coordinate → usually stacked with 90º rotations
- If all the charge is collected in one wire the resolution is determined by the wire spacing
- Charge sharing among wires → better resolution

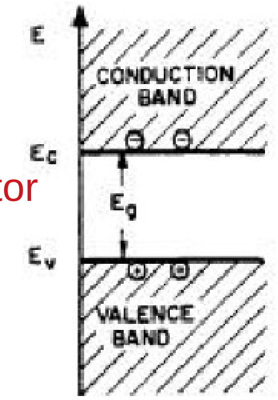
$$\sigma_x = \frac{d}{\sqrt{12}}$$



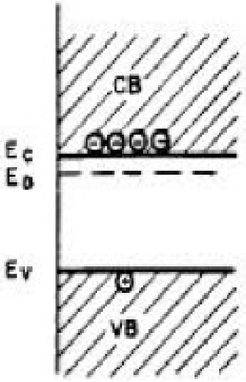
An example: Sillicon p-n diodes (I)

- Semiconductor materials have a very particular energy band structure:
  - The valence and the conduction bands are relatively close together
  - The conduction band is empty but thermal excitations can easily populate it
- A particle crossing the semiconductor ionizes moving states from valence to conduction
  - On average a MIP produces about 10000 electron/hole pairs every 100 microns
- The problem is that in the conduction band there are other sates promoted thermically
  - We can get rid of those by using the properties of “n-type” and “p-type” doping
  - A semiconductor doped with donor atoms (n-type) easily donate electrons to CB
  - A semiconductor doped with acceptor atoms (p-type) easily accept electrons from the VB

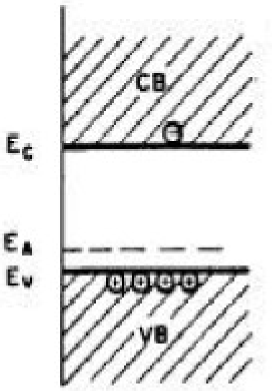
Intrinsic semiconductor



n-type doped semiconductor

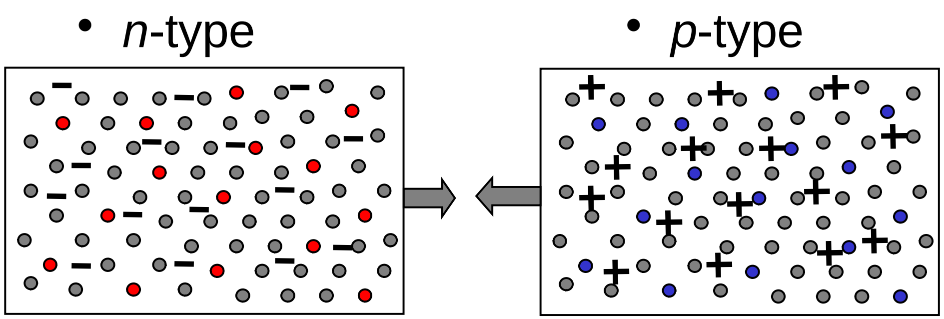


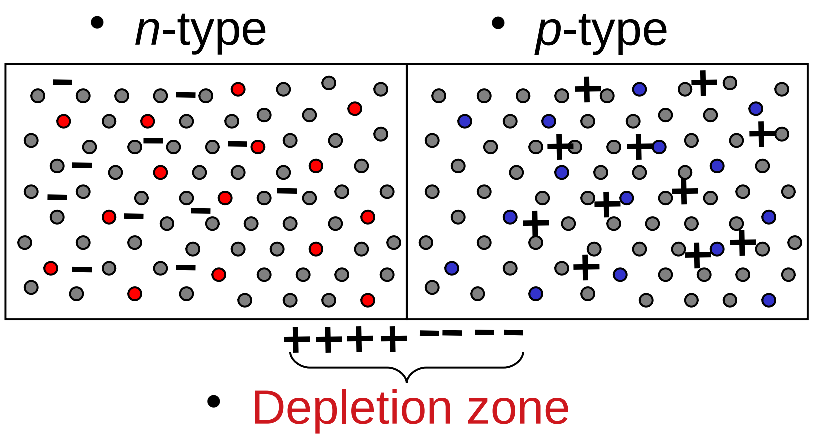
n-type doped semiconductor



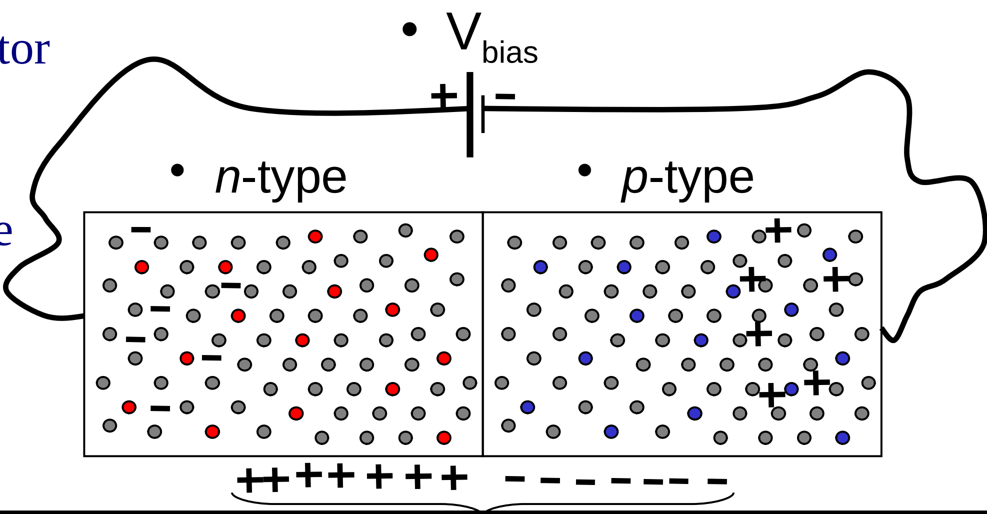
An example: Sillicon p-n diodes (II)

- In a p-n junction there is a diffusion process of electrons and holes creating an electric field



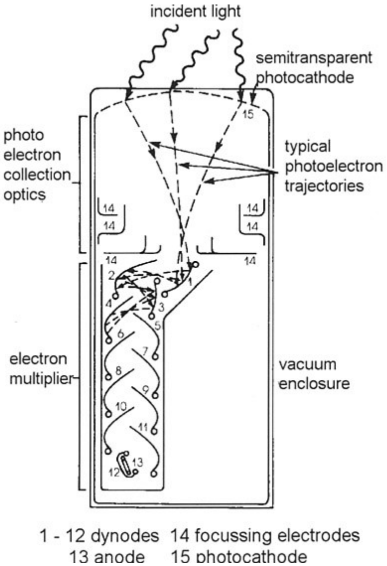


- The electric field removes any free charge carriers creating the so called “depletion zone”
- The size of the depletion zone can be increased by adding a reverse bias voltage
- The depletion zone acts as a particle detector
- The carriers created by a crossing particle will produce a detectable current due to the electric field



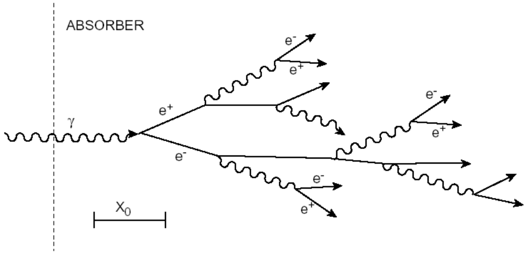
Basic detection techniques: photo-detection

- Charged particles can produced light through several mechanisms
  - Bremstrahlung (combined with pair production) → scintillators
  - Cherenkov light
  - Transition radiation
- The light produced is collected with photomultipliers
  - Photo-multiplier tubes
  - Semi-conductor based (photo-diodes)



An example: scintillator crystals

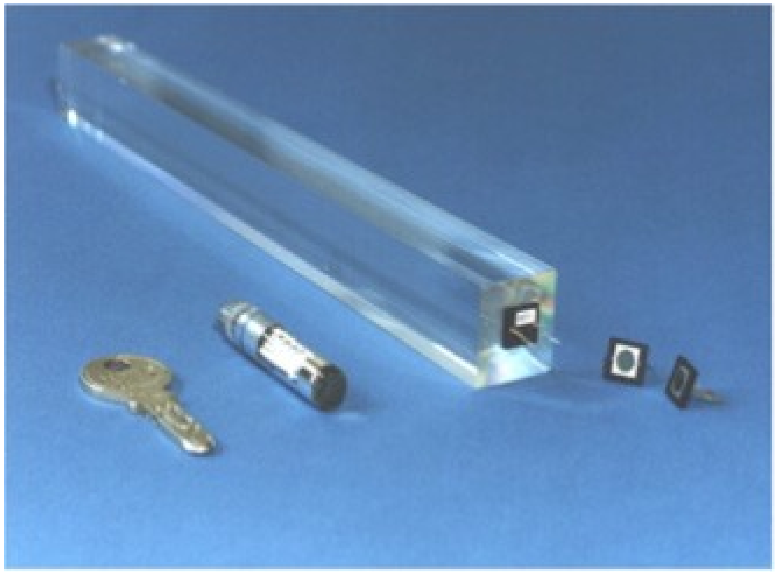
- Charged particles crossing dense materials produce photons via Bremsstrahlung
- High energy photons crossing dense materials create e^-e^+ pairs
- In dense crystal scintillators this process occurrs in a sort of chain reaction
  - Producing a so-called electromagnetic shower
  - It stops when the energy of the photons is < $2m_e$



- The crystals conduct the light towards the photomultiplier
- In modern detectors photomultiplier are based on avalanche photodiodes technology

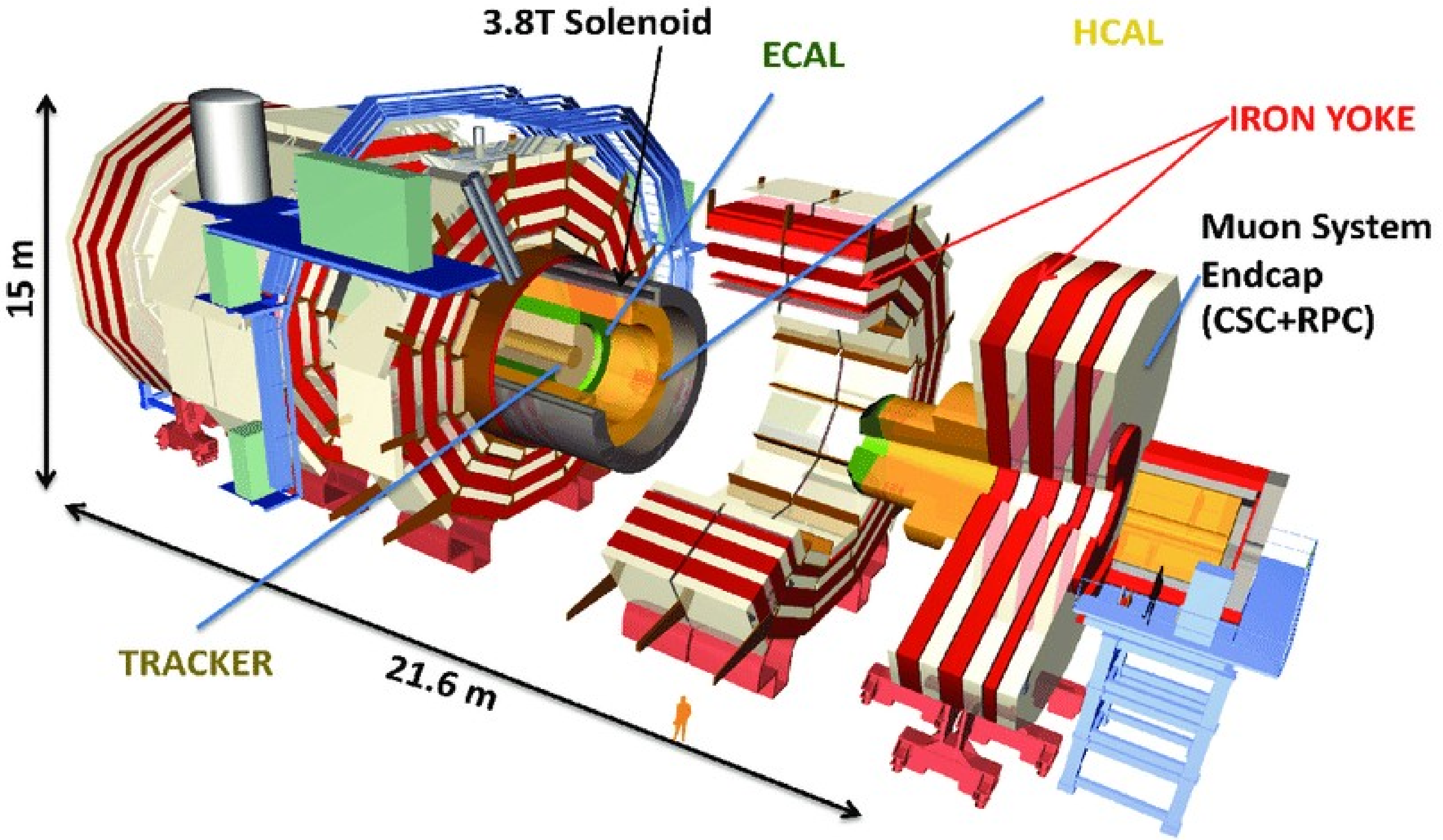
- **CMS ECAL: 80,000 $PbWO_4$ crystals**
- **Avalanche photodiodes measure scintillation light**

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

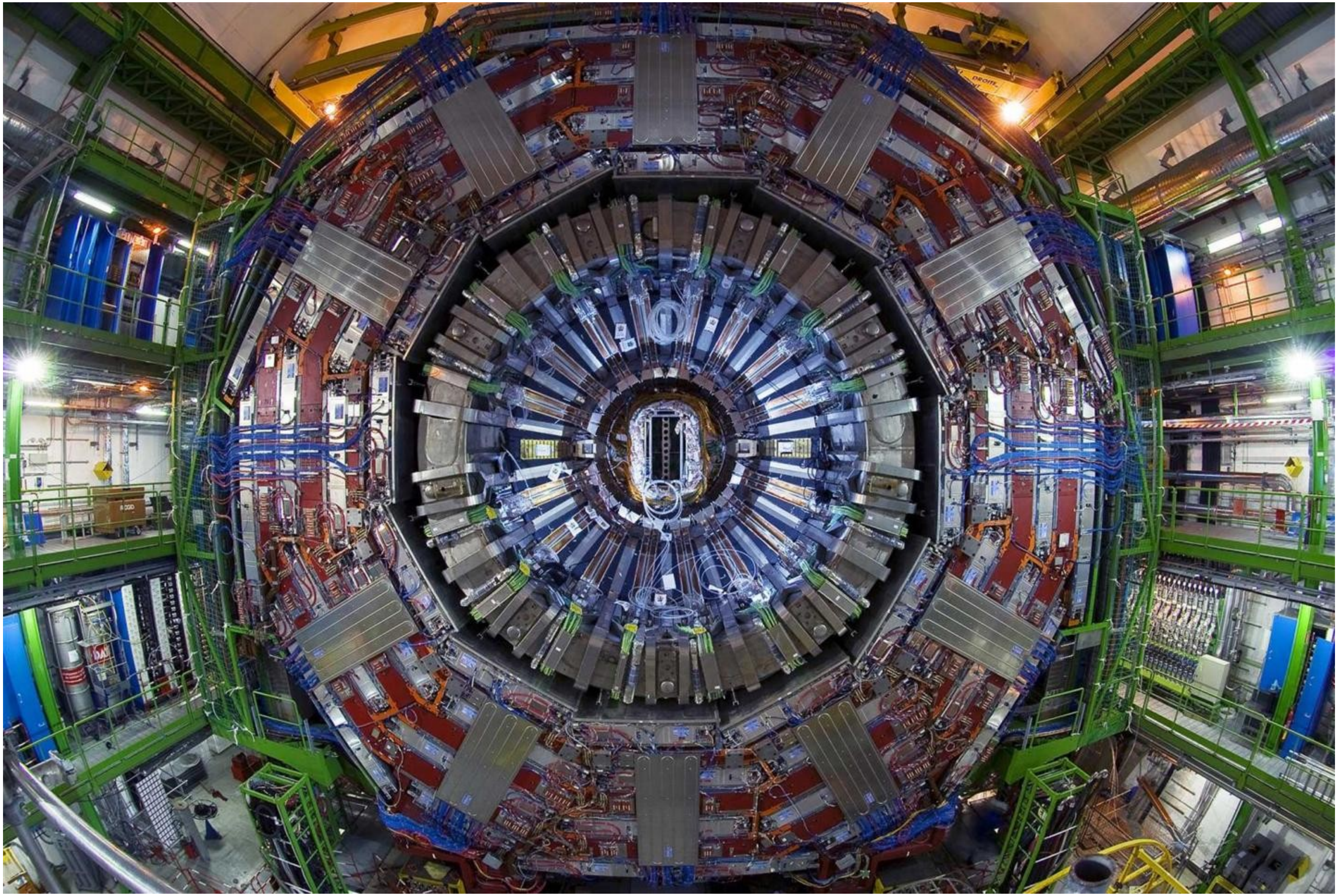


Large Particle Detectors (I)

- Modern detectors use several technologies to detect different kinds of particles

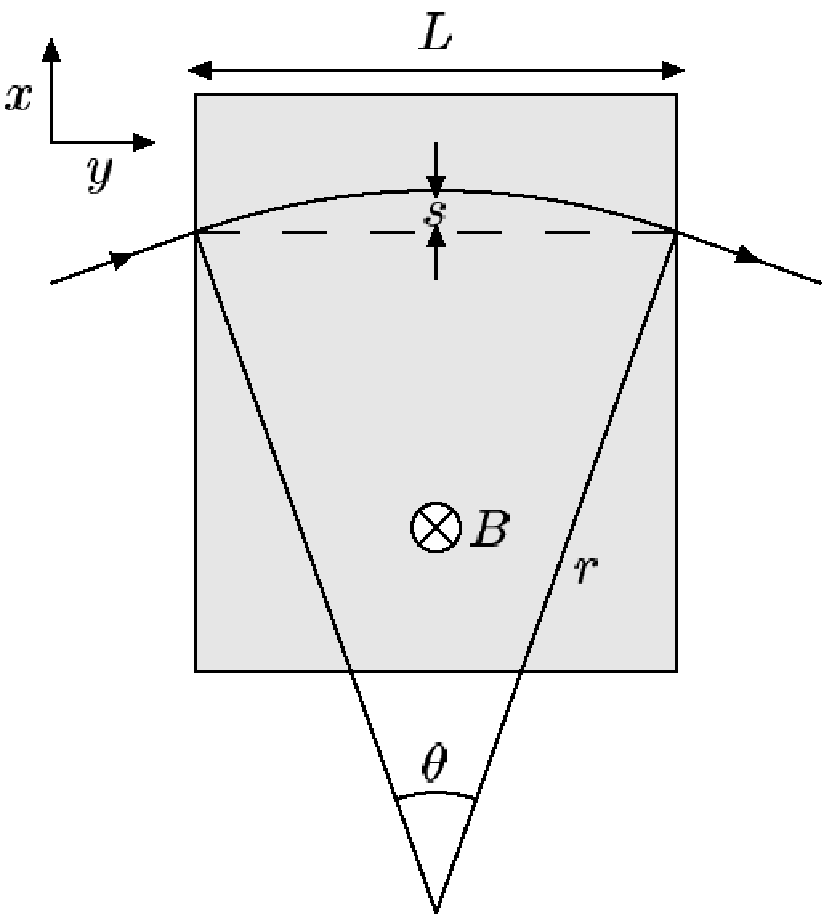


Large Particle Detectors (II)



Large Particle Detectors: momentum measurement

- The momentum of charged particles in large detectors is measured using magnetic fields
  - Charge particles bend in a magnetic field → the more momentum the less bending



Magnetic force: $\vec{F} = q(\vec{v} \times \vec{B})$ or $|F| = qv_{\perp}B$

Centrifugal force: $|F| = \frac{mv_{\perp}^2}{r}$

Radius: $r = \frac{mv_{\perp}}{qB} = \frac{P_{\perp}}{qB}$,

$r = \frac{P_{\perp}}{0.3B}$ ($P_{\perp}$ in GeV/c and B in Tesla)

Bending angle: $\frac{\theta}{2} \approx \sin\frac{\theta}{2} = \left(\frac{\mathrm{L}/2}{r}\right) \Rightarrow$

$\theta \approx \frac{0.3BL}{P_{\perp}}$

Sagitta:

$s = r - r\cos\frac{\theta}{2} = r\left(1 - \cos\frac{\theta}{2}\right) \approx r\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{BL^2}{P_{\perp}}$

Large Particle Detectors: particle identification

- Information from different sub-detectors can be mixed to identify the particles