Universität Zürich[UZH]

Physik-Institut

# Kern- und Teilchenphysik II
# Lecture 10: Interaction of Matter with Particles

(adapted from the Handout of Prof. Mark Thomson)

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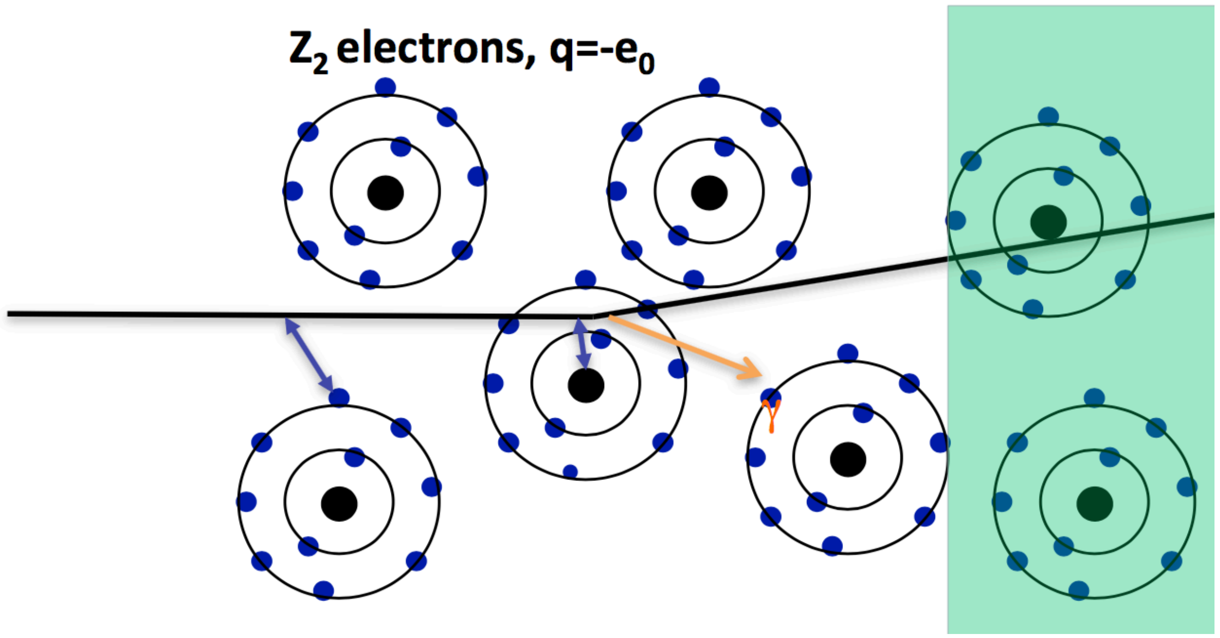
http://www.physik.uzh.ch/de/lehre/PHY213/FS2017.html

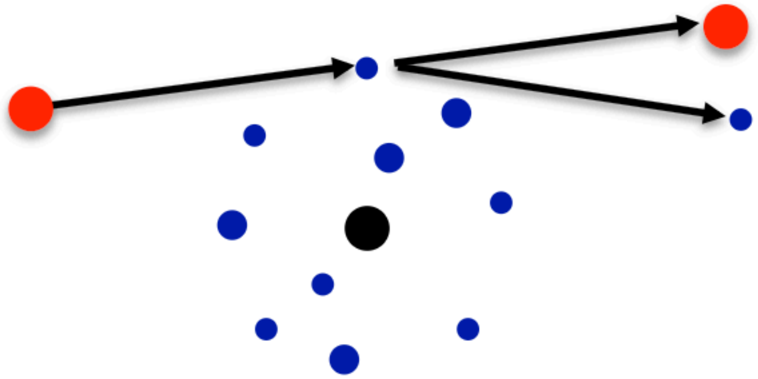
# Charge particle Interactions




Charged particle traversing a material have three effects:

- The particle loses energy by interacting the electrons and exciting or ionising the atoms
- The particle can be deflected by the nucleus (in general much heavier) multiple scattering, a bremsstrahlung photon can be emitted in this process
- If the particle velocity is larger than the speed of light <u>in the medium</u> Cherenkov light is emitted

# Energy loss

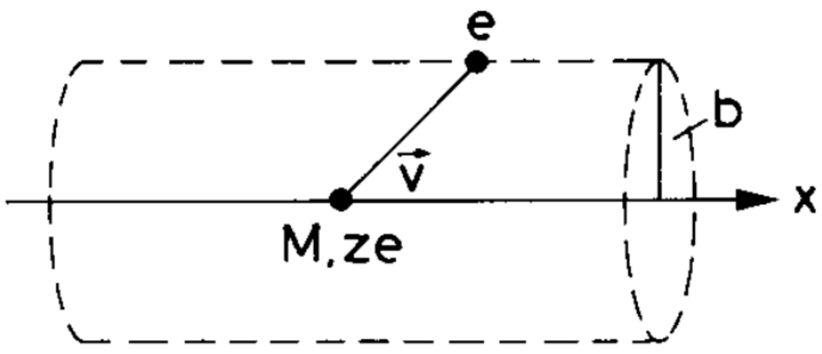



- Let's first consider the M>>$m_e$ , energy loss for electrons is more complicated
- The trajectory of the particle is approximately unchanged after scattering with electrons
- The energy loss is given by

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} ln\left(a\beta^2\gamma^2\right)$$

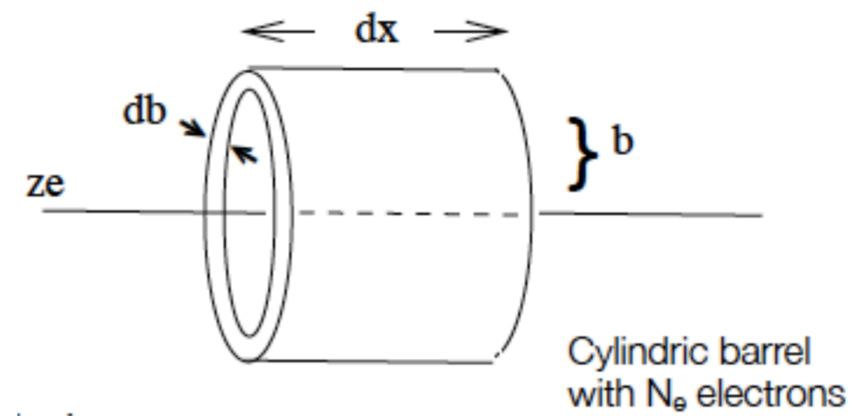
- $Z$: atomic number
- $\beta,\ \gamma$: relativistic factors
- $a$: material-dependent constant

# Bohr derivation




Particle with charge Ze and velocity v moves through a medium with electron density n.

$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$




$$F_\perp = eE_\perp \rightarrow \Delta p_\perp = e\int E_\perp \frac{dx}{v} = \frac{2ze^2}{bv}$$

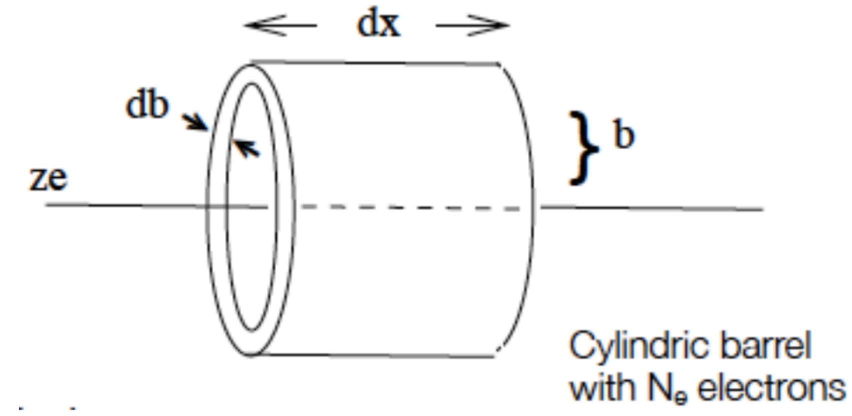
Where Gauss theorem implies $\int E_\perp (2\pi b) dx = 4\pi (ze)$

The energy transferred to a single electron is given by $\Delta E = \frac{\Delta p_\perp^2}{2m} = \frac{2z^2e^4}{(b^2v^2)m_e}$

# Energy loss

For n electrons distributed on a barrel

n = $N_e$ (2πb) db dx




$$dE = -\frac{\Delta p_{\perp}}{2m_e} 2\pi N_e b \cdot db \cdot dx = -\frac{4\pi N_e z^2 e^4}{m_e v^2} \frac{db}{b} dx$$

$$r_e m_e c^2 = e^2$$

Stopping power:

$$-\frac{dE}{dx} = \frac{4\pi N_e z^2 e^4}{m_e v^2} \int_{b_{min}}^{b_{max}} \frac{db}{b} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} ln \frac{b_{max}}{b_{min}}$$

This formula diverges for $b_{min}$ -> 0, we can set the minimum and the maximum value to b by using heuristic arguments

# Energy loss

We have now to determine the $b_{min}$ and $b_{max}$ factor:

- $b_{min}$ is for heads-on collisions, the energy loss we have

$$E(b_{min}) = \frac{(2z^2e^4)}{m_e v^2 b_{min}^2}$$

Energy loss by a massive projectile M>>$m_e$

for $b_{min}$ the lost energy is maximal $E_{max} = 2\gamma^2 v^2 m_e = 2m_e c^2 \beta^2 \gamma^2$

- Electrons are bound in atoms with an average orbital frequency of $\langle \nu_e \rangle$, the interaction has to happen in a minimum time T comparable to the electron orbital frequency $b_{max} = \frac{\gamma v}{\langle \nu_e \rangle}$

- $b_{max}$ also corresponds to the distance at which the kinetic energy transferred corresponds to $E_{min}$ = I (mean ionisation potential)

$$-\frac{dE}{dx} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} ln \frac{\gamma^2 m v^3}{z e^2 \langle \nu_e \rangle} = \frac{4\pi N_e z^2 r_e^2 m_e c^2}{\beta^2} ln \left( \frac{2m_e c^2 \beta^2 \gamma^2}{I} \right)$$

# Bethe-Bloch equation

The Bethe-Bloch formula is valid for projectile with mass $M \gg m_e$, e.g. p, K, pi, mu, …

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

$$(2\pi N_a r_e^2 m_e c^2) = 0.1535 \cdot MeV\, cm^2/g$$

Absorver dependent quantities

$\rho$ : density of absorber    Z, A: atomic number and weight of the absorbed

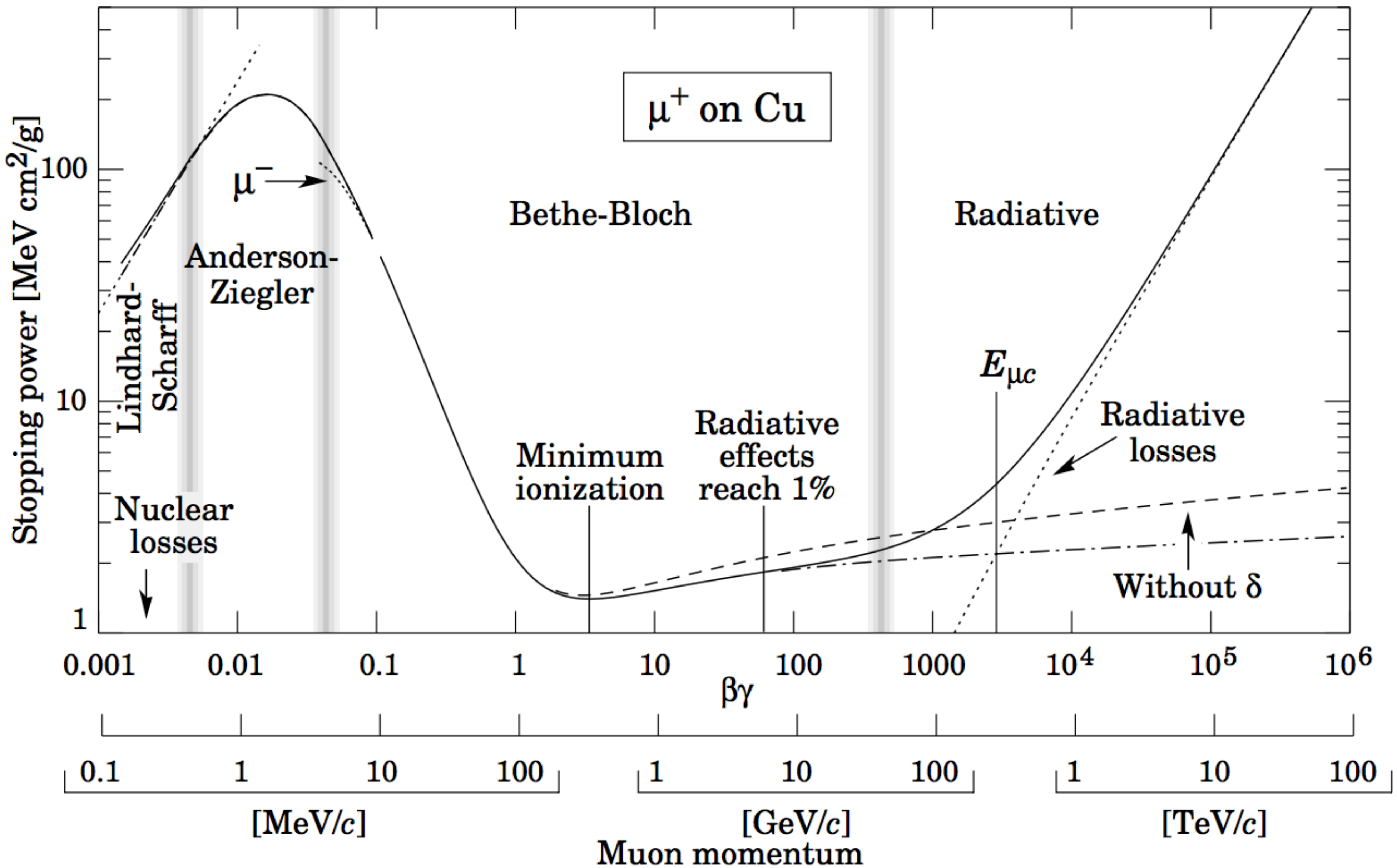
I: mean ionisation potential    $\delta$ : density correction, $C$ : shell correction

Incident-particle-dependent quantities

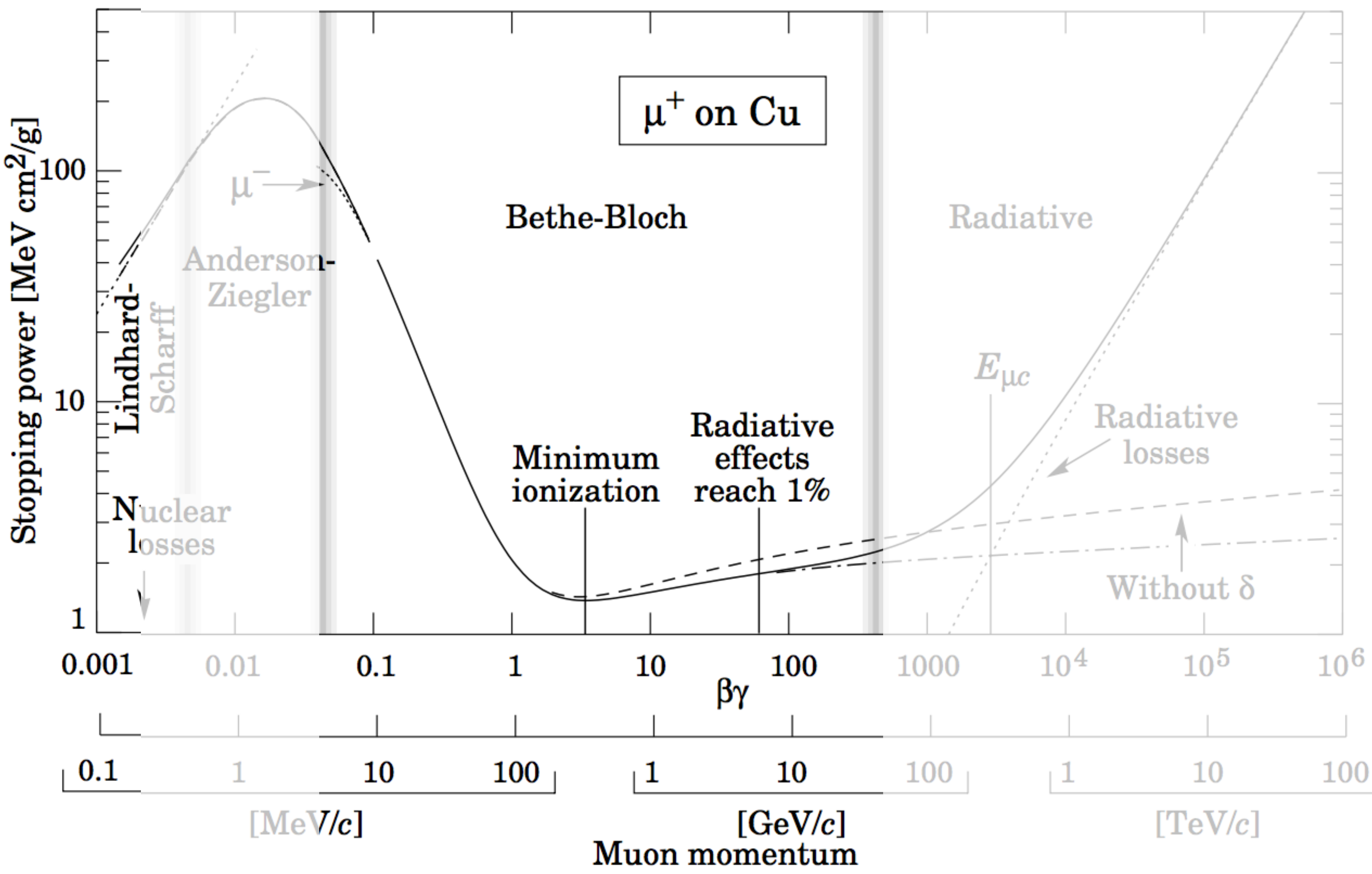
$\beta = \frac{v}{c}$ of incident particle, $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

$W_{max}$ = max energy transferred in one collision, $z$ = charge of the projectile

# Bethe-Bloch equation



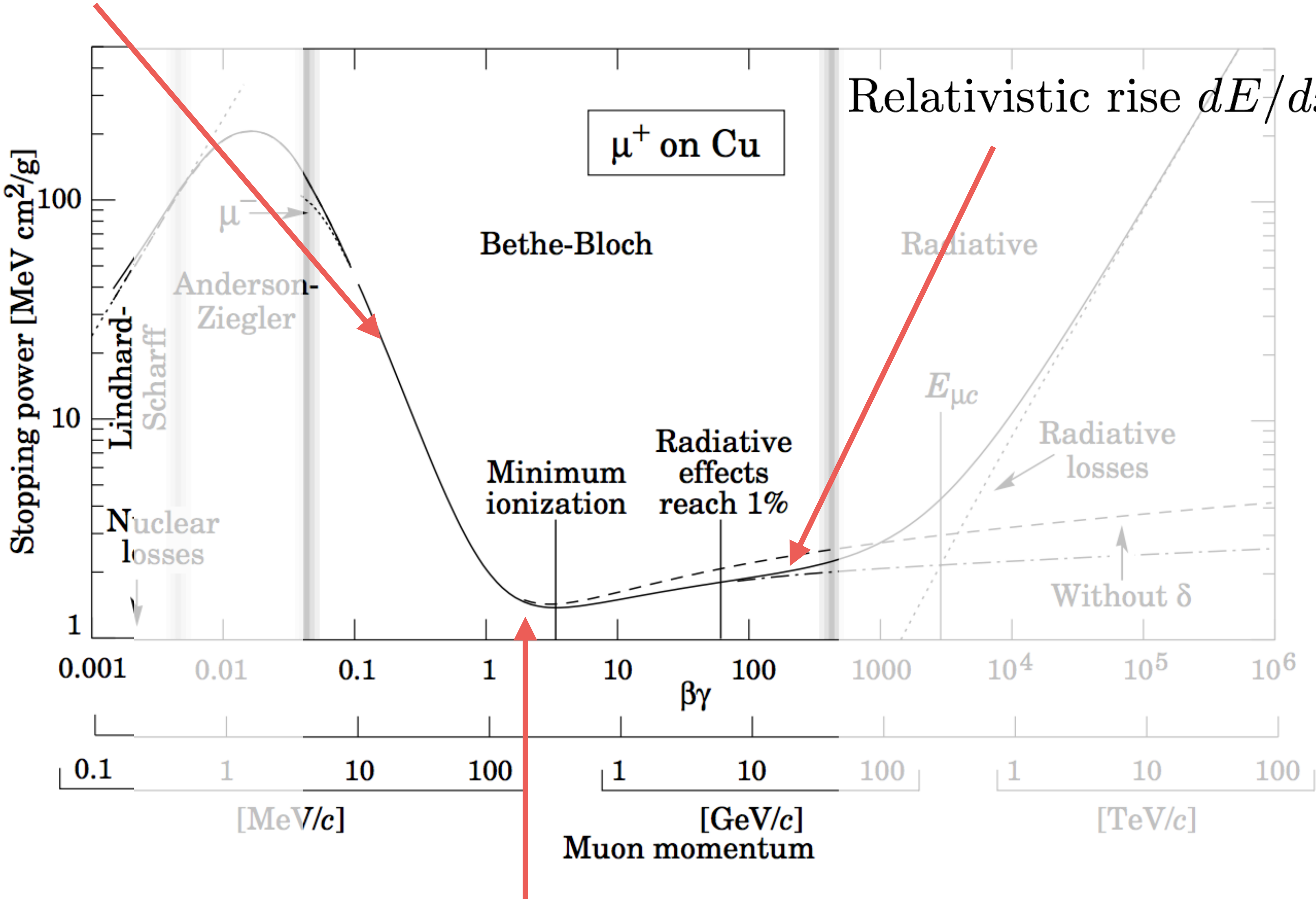
# Bethe-Bloch equation



# Bethe-Bloch equation

Initial fall $dE/dx \propto \beta^{-2}$

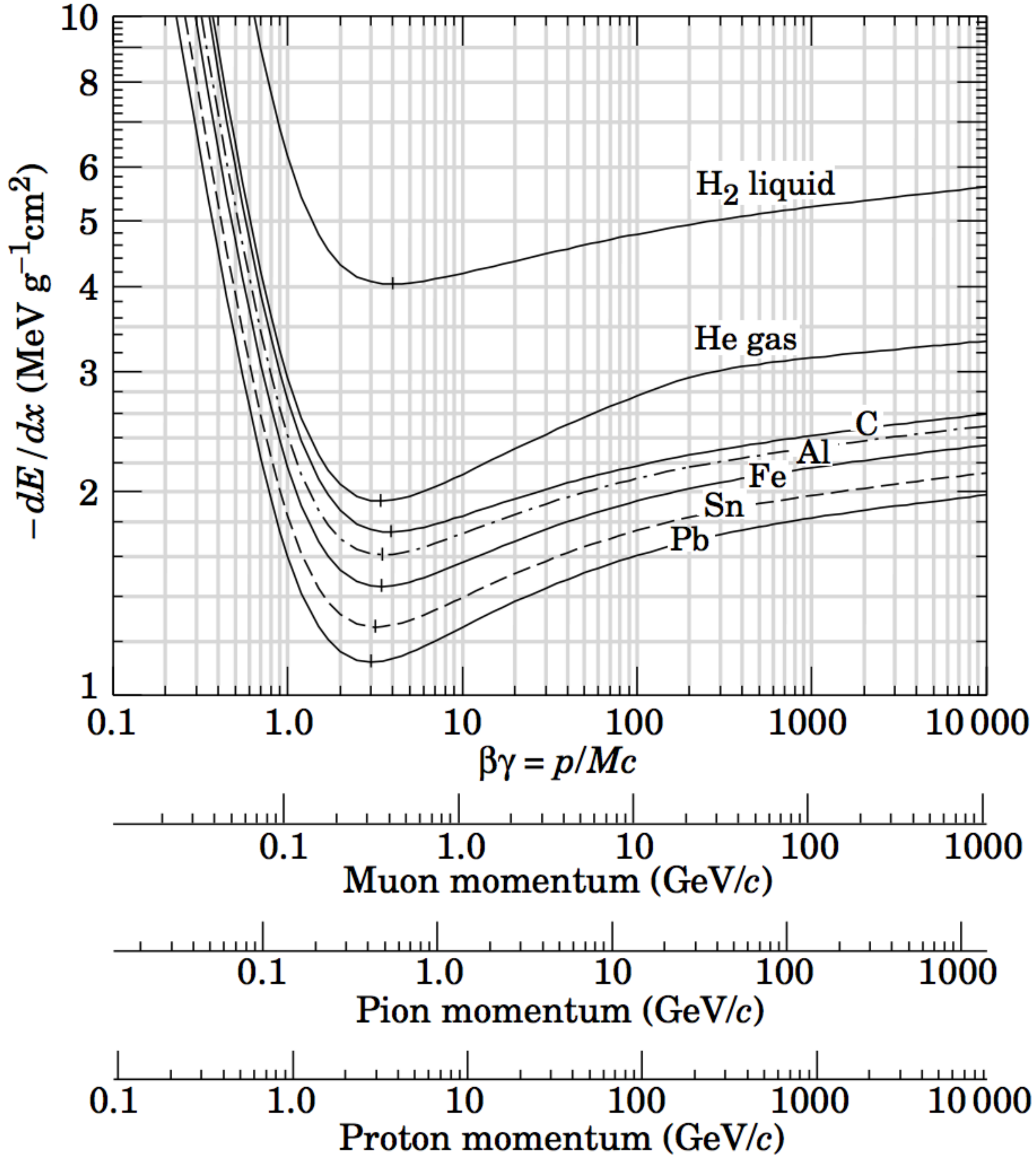
Relativistic rise $dE/dx \sim ln(\beta\gamma)^2$

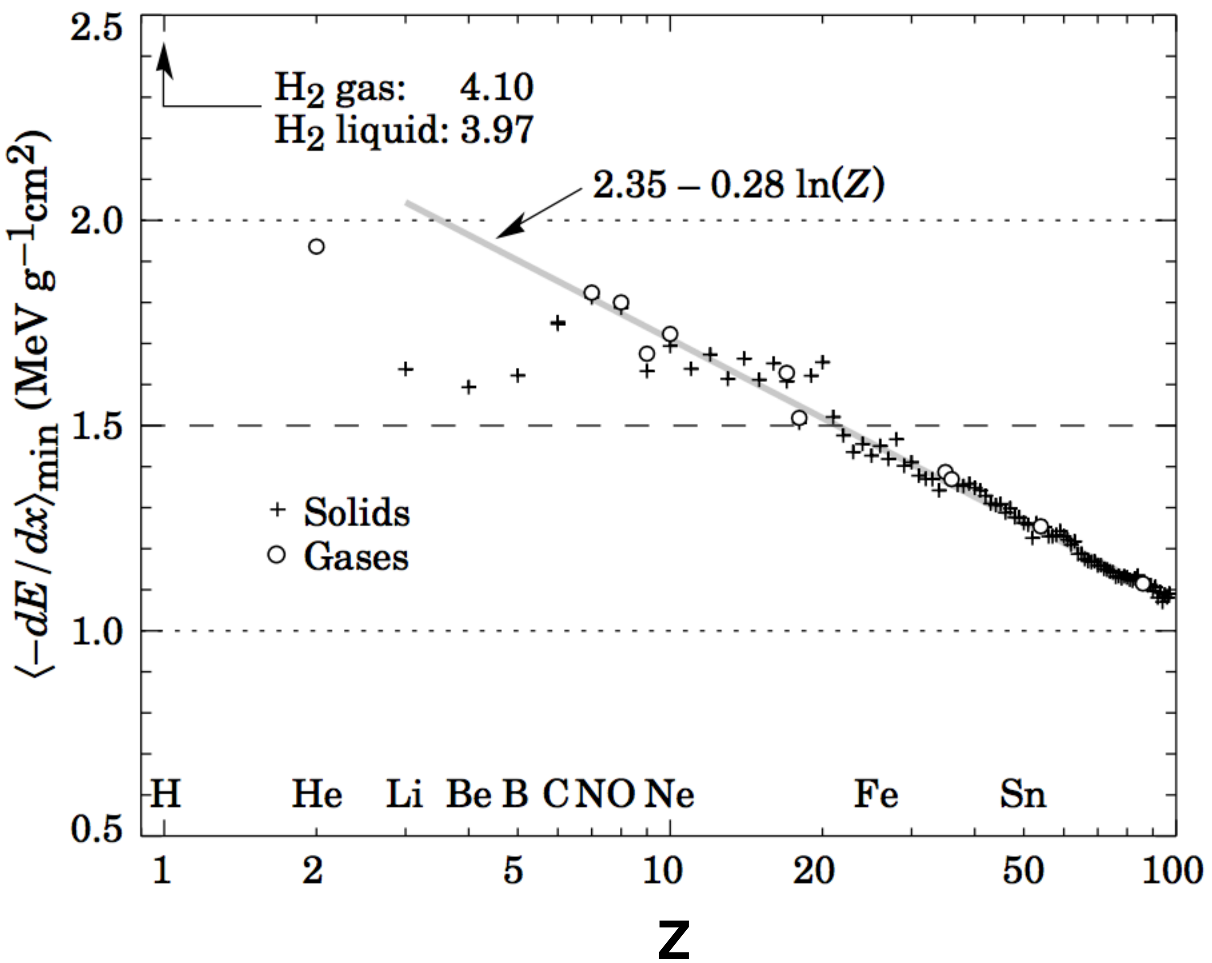



$\beta\gamma = 3-4$ minimum ionizing particle (MIP)

# Dependence on Z and A

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



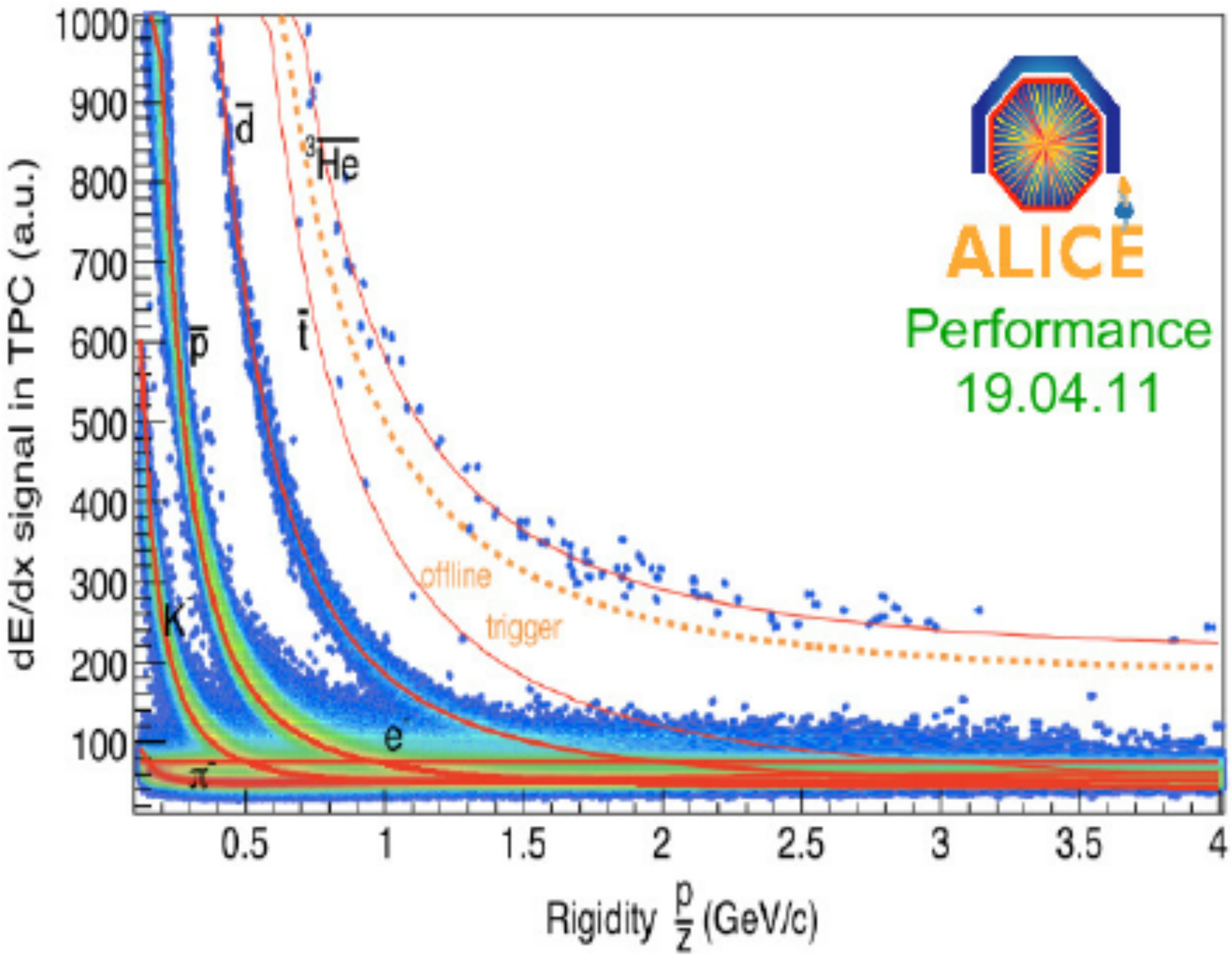
# Examples

- A MIP has looses about $1 - 2\frac{MeV}{gcm^2}$
- A MIP therefore looses about 1-2MeV/cm in a material with density $1\frac{g}{cm^3}$

Calculate the energy lost by a 10GeV muon in a 100 cm of iron

- $\rho = 7.87g/cm^3,\ L = 100cm$
- $\Delta E \simeq 1.4\frac{MeV}{gcm^2} \times 100cm \times 7.87\frac{g}{cm^2} = 1102MeV$

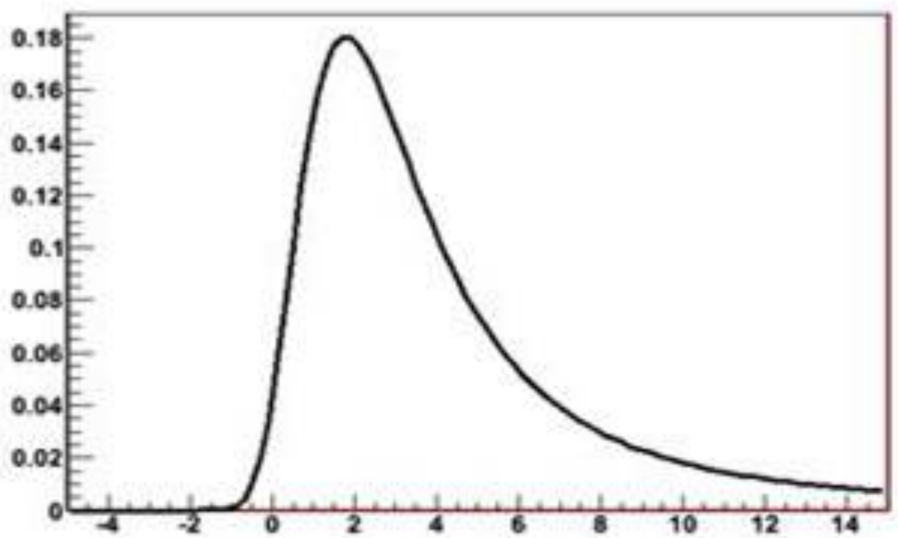
# dE/dx for Particle ID

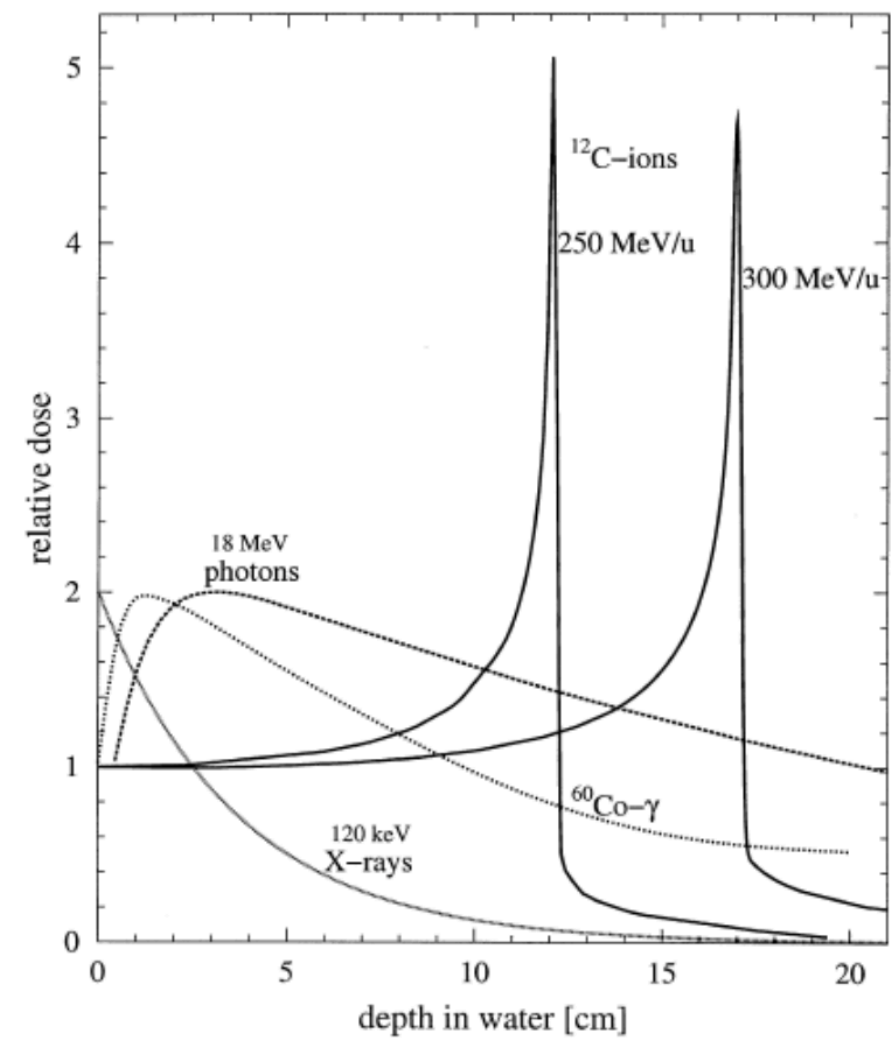



- The momentum is measured by the deflection in a magnetic field
- By measuring also the energy loss in a medium we can identify the particle

# Energy loss by a particle

- The average energy loss of a particle in a material is described by the Bethe-Bloch formula
- When a single particle pass through a material the energy loss is a stochastic process described by a Landau distribution

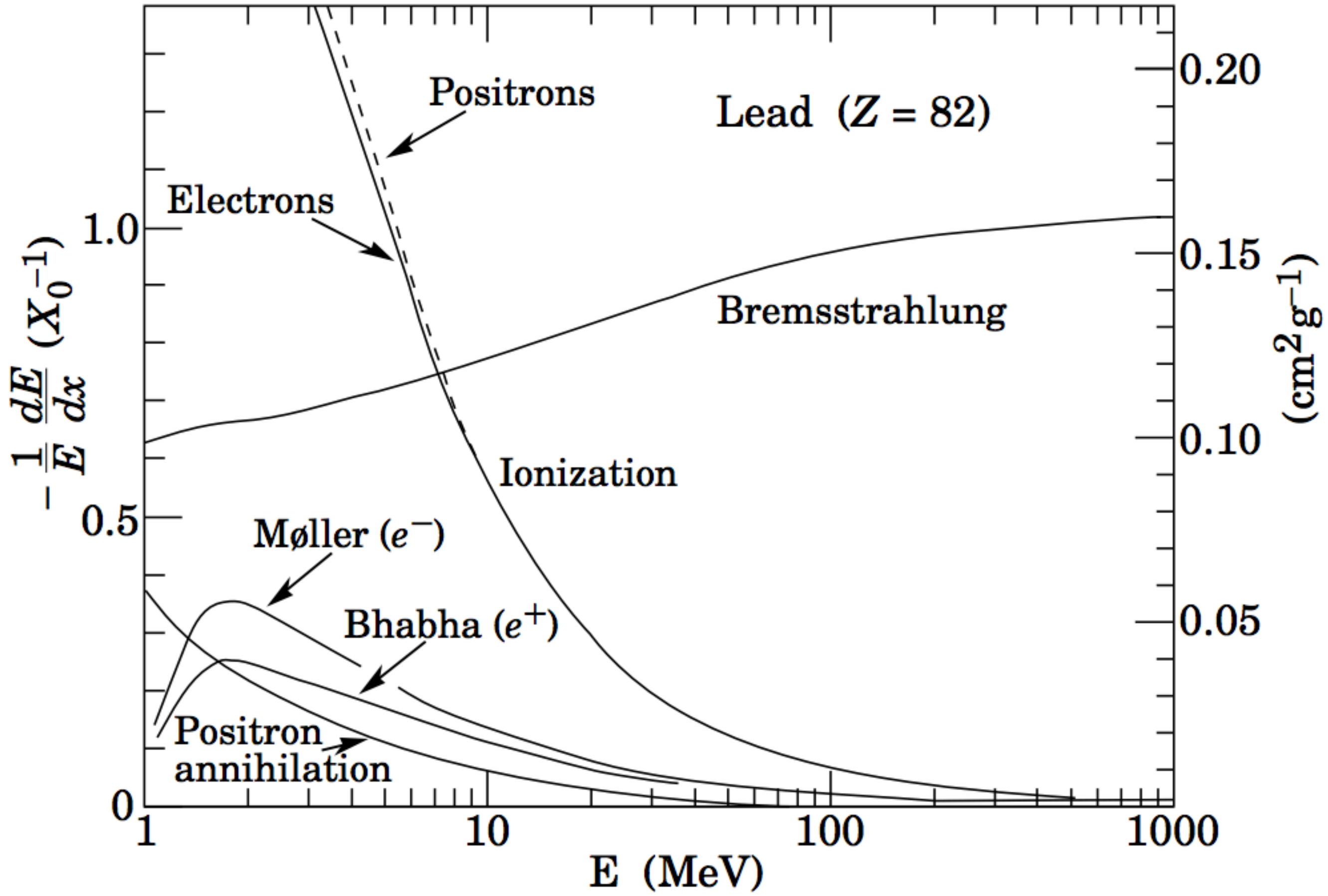


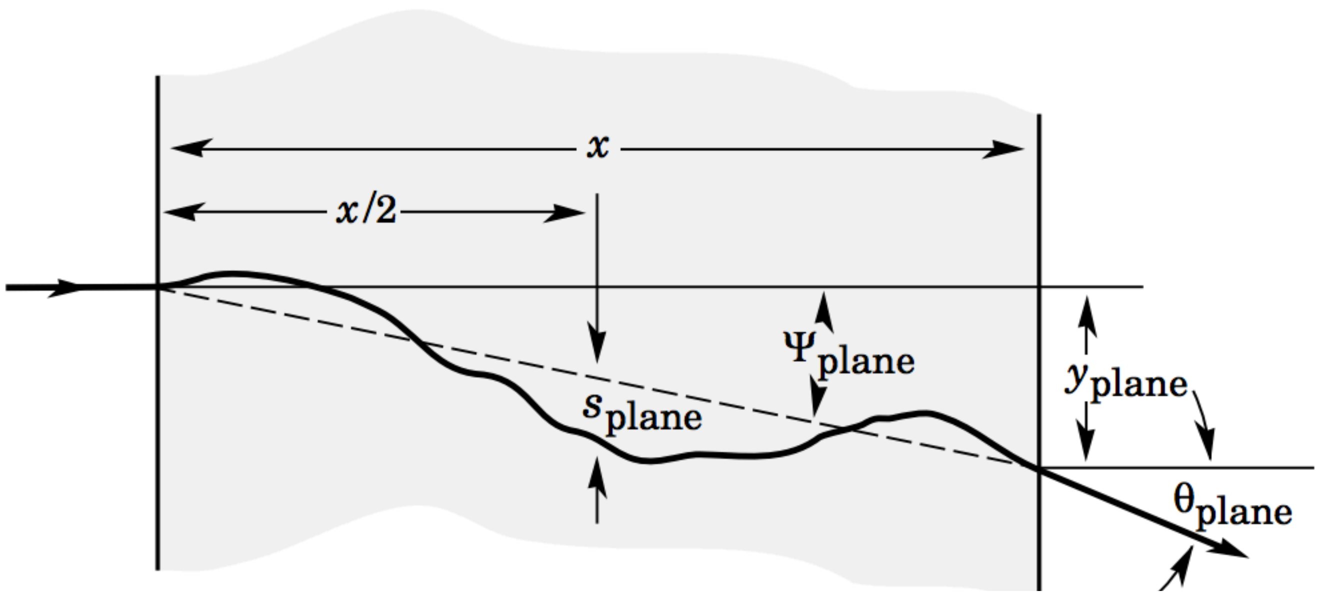

- Most of the energy is lost by the particle at low $\beta\gamma$
- Therefore most of the energy is lost in the final part of the trajectory, this is known as Bragg peak and it is important for hadron therapy of tumor

# Energy loss for electrons

- If we consider electrons passing through a material the Bethe-Bloch formula needs to be modified for the scattering of undistinguishable particles
- The approximation $M \gg m_e$ cannot be applied anymore
- At energies larger than ~30MeV the main process is the bremsstrahlung, which is proportional to $E/m^2$, therefore is small for heavier particles



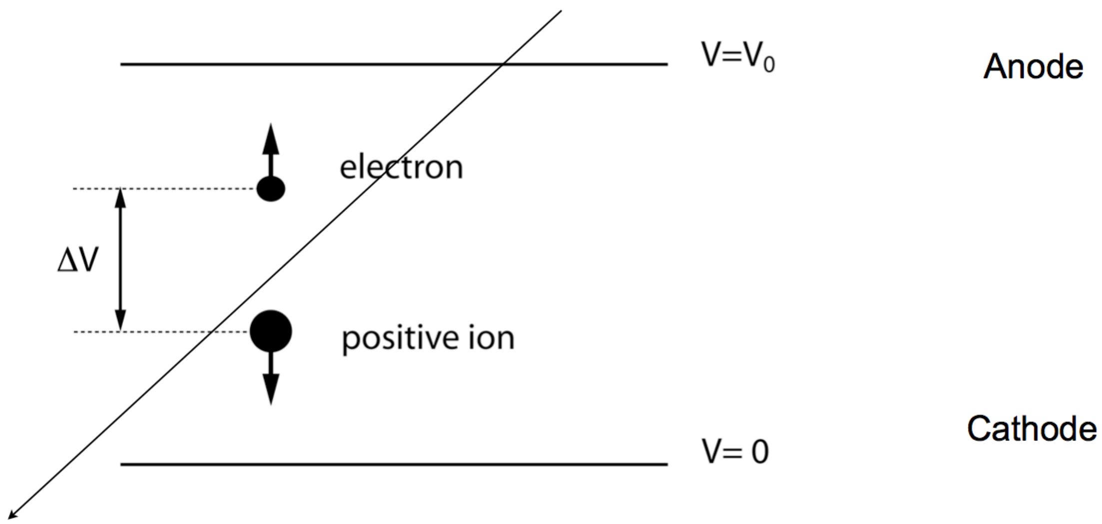
# Multiple Scattering

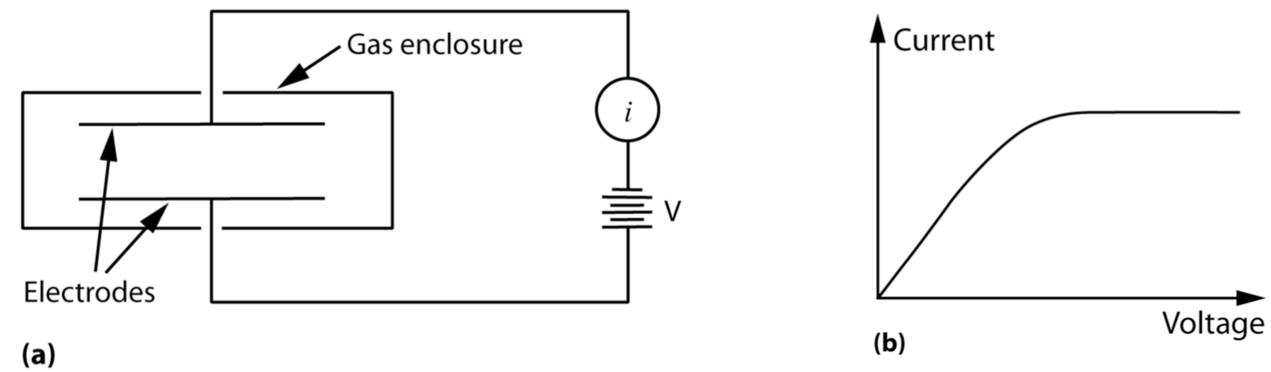



- When a charged particle traverse a medium is deflected by the interaction with the charged nuclei
- This effect is known as Coulomb multiple scattering
- It is an important effect that needs to be taken into account in tracking
- The rule of thumb is that tracking stations should have the least material as possible to minimise multiple scattering, and make precise measurements of momenta

# Gas Detectors

- When a charged particle passes through a gas it ionises
- If there is a DV the electron are collected at the anode and ions at the cathode
- The current generates a signal that is read by the electronics

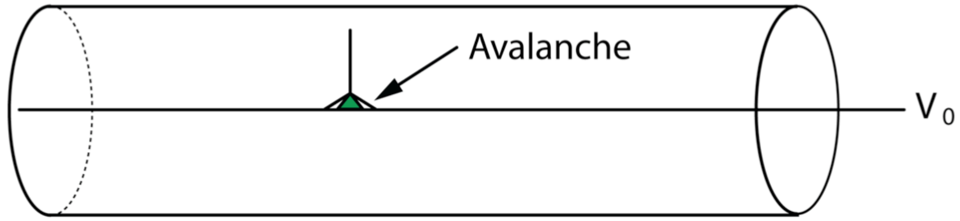



- Gas detectors often use a nobel gas (e.g. Ar, Ne, ..) and a quenching gas (e.g. $CO_2$)
- The nobel gas is ideal to avoid the formation of free radicals
- The quenching gas to absorbe UV photons that can be emitted by the excitation

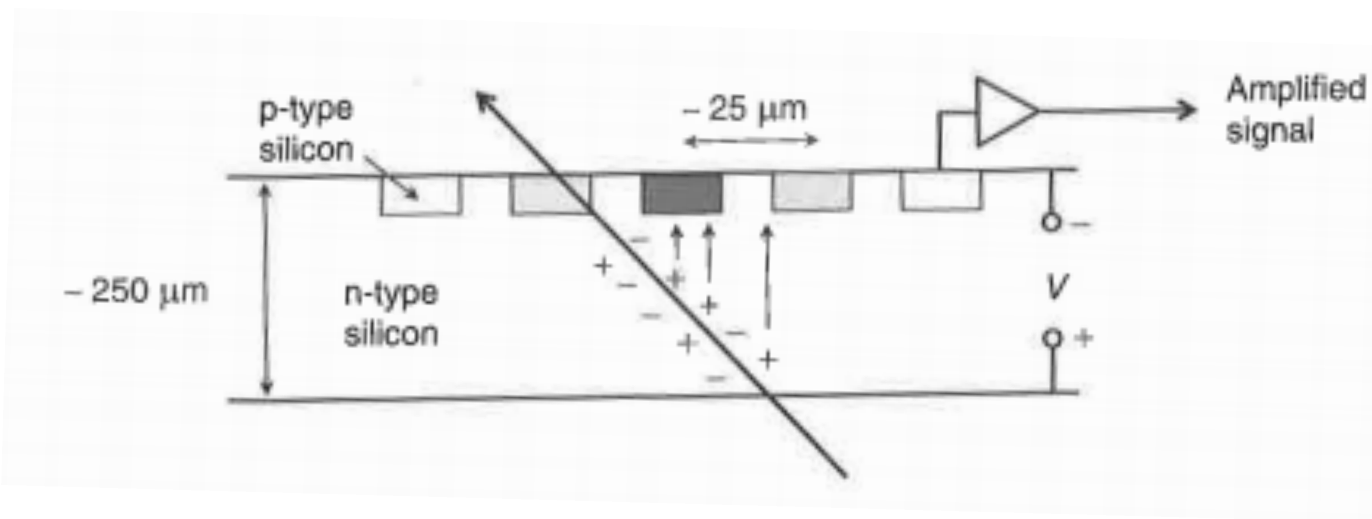
# Gas Detectors

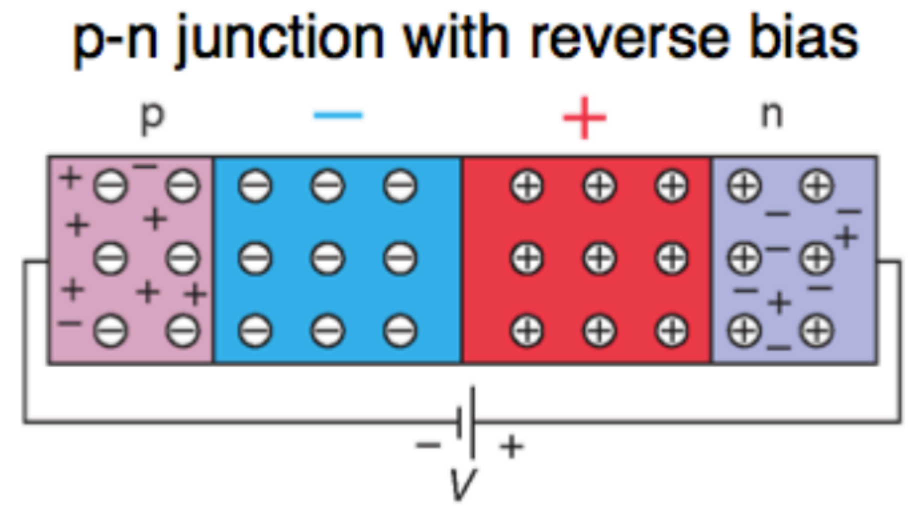
- There are different kind of gas detector: Drift Chambers, Multiwire proportional chambers (MWPC), GEM detectors, …




- Normally some kind of multiplication is used, e.g. using the increased field close to the anode, otherwise the signal is too small
- Gas detector are often used as tracking detectors since the particles is almost unperturbed by the interaction with the material (low material budget)
- Often several layers with stereo angles are used to measure the 3d position of the particles
- The drift time of the electrons provide additional information that contributes to the resolution

# Silicon Detectors




- Silicon detectors consists of p-n juction with a relatively large voltage applied

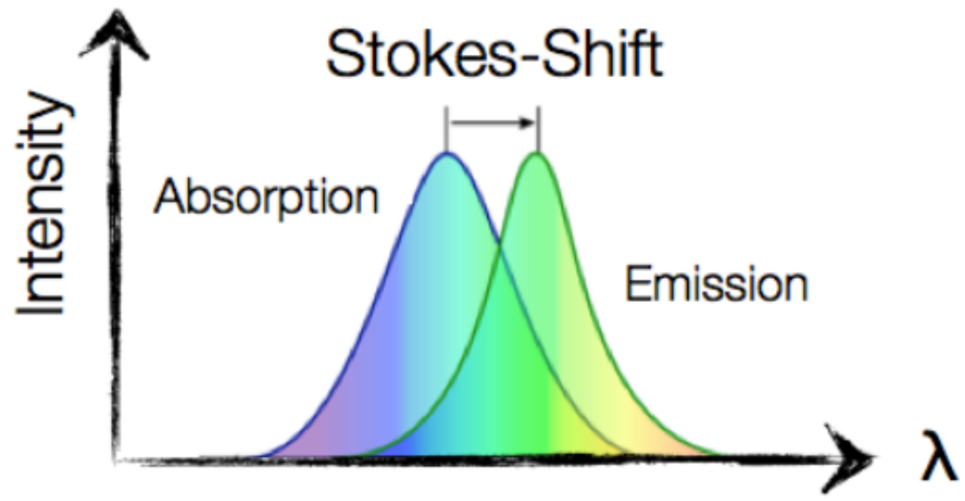
- When a charged particle passes through the bulk it creates electron-hole pairs that drift in the electric field of the silicon detector and creates a signal

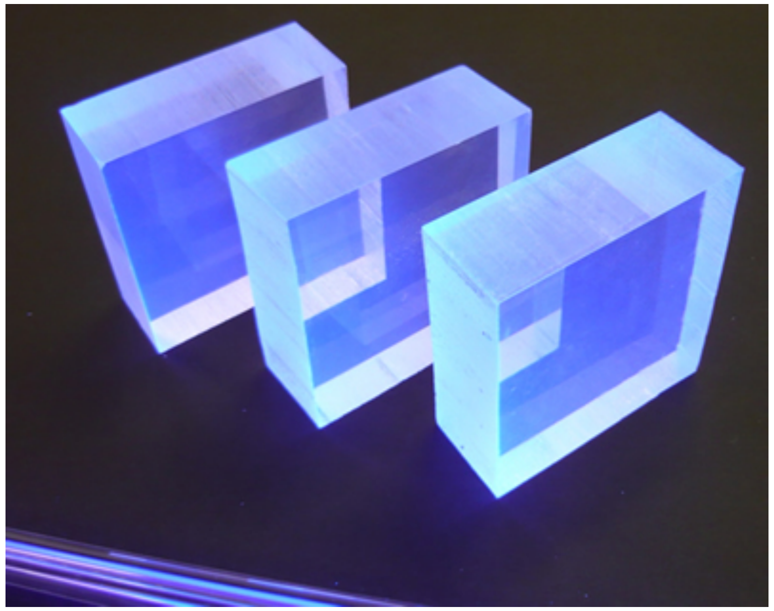
- Silicon detectors can be strip microstrip or pixel detectors

- At LHCb they are normally used in the regions closer to the vertex where there is large occupancy and high precision is needed

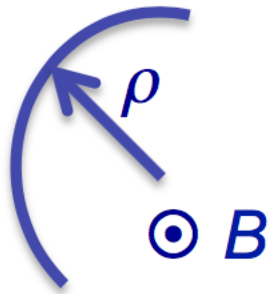
# Scintillators

- Charged incident particles or photons excited atoms in scintillating medium
- Excited states decay to a “metastable” state under the emission of photons, which is then detected by a PMT or a SciPM
- Since the excitation decay happens to an intermediate state there is not complete overlap between the absorption and emission spectrum, i.e. the scintillator is transparent
- There are organic (Naphtalene, Antracene, …) and inorganic scintillators (LiquidArgon, Liquid Xenon, Sodium iodide)



# Momentum Measurements



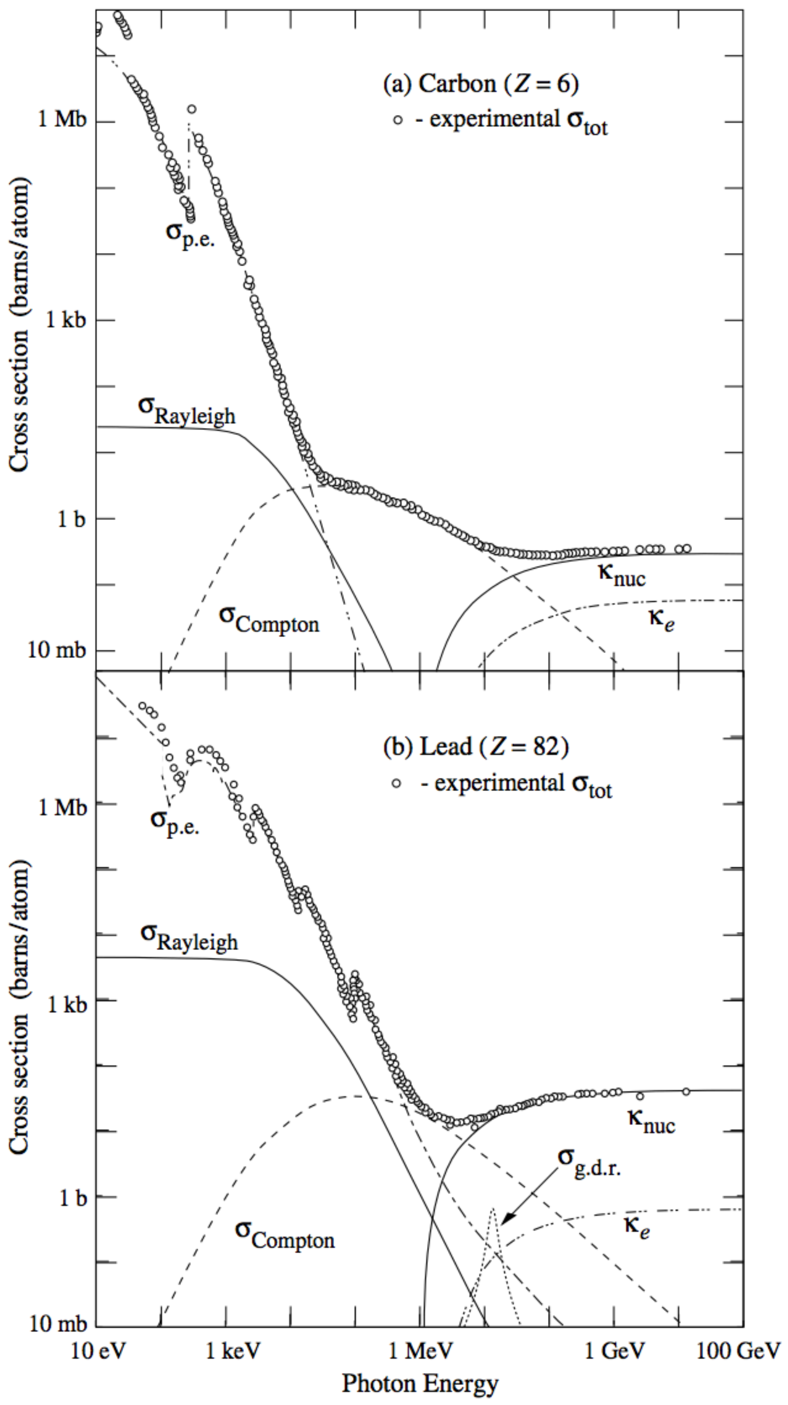

- Lorentz Force: $\overline{F} = q\overline{v} \times \overline{B}$
- In the plane: $F = qvB = m\frac{v^2}{\rho} \rightarrow B\rho = \frac{p}{q}$

- Momentum measured using magnetic spectrometer
- Measurement of the curvature in the magnetic field using tracking stations and knowing the magnetic field
- Important to have low material budget before the momentum measurement to minimise multiple scattering
- Uncertainty on the momentum depends on the uncertainty on the curvature and the map of the magnetic field

# Interaction of photons with matter

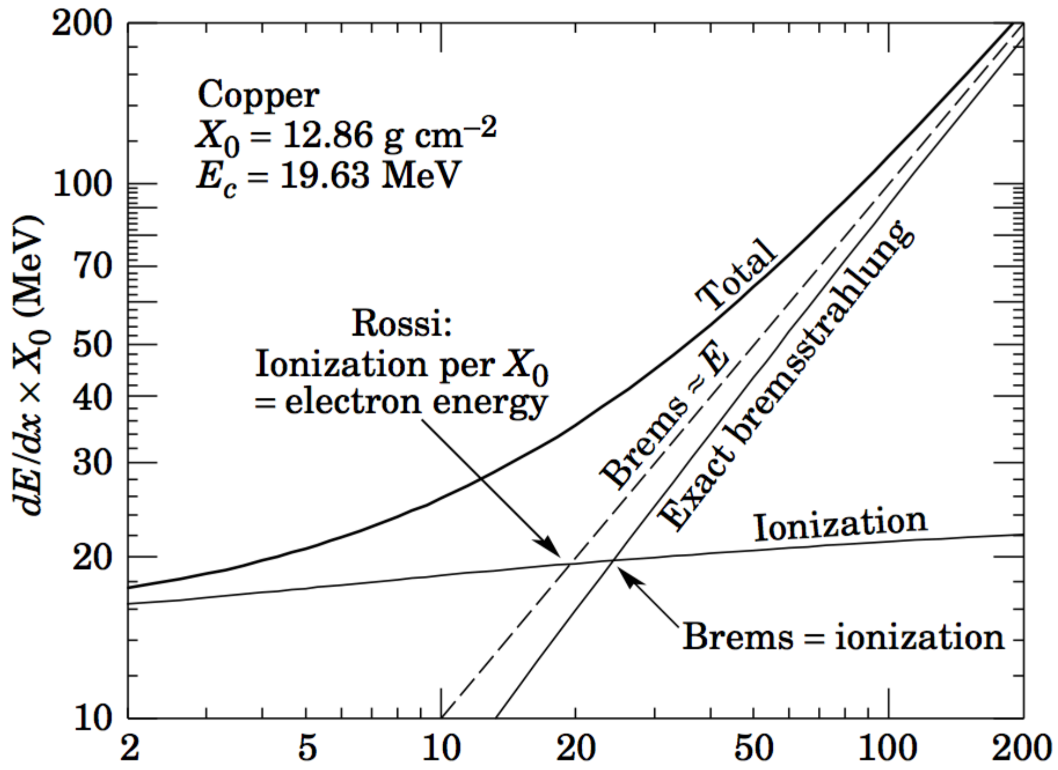
Photons interact in three possible ways

- Photoelectric effect:
  - Photon absorbed by electrons of the atoms
  - Dominates at low energies
- Compton scattering
  - Elastic scattering between photon and electrons
  - Important at intermediate energies
- Pair production:
  - When the energy of the photon is large enough to produce an electron-positron pair, this process dominates



# Energy loss

- At low energies electrons loose energies via ionisation
- There is a minimum where they are MIP
- After the energy loss by ionisation increases logarithmically, while the bremsstrahlung
- The critical energy $E_c$ is the energy for which the energy loss by ionisation and bremsstrahlung are the same



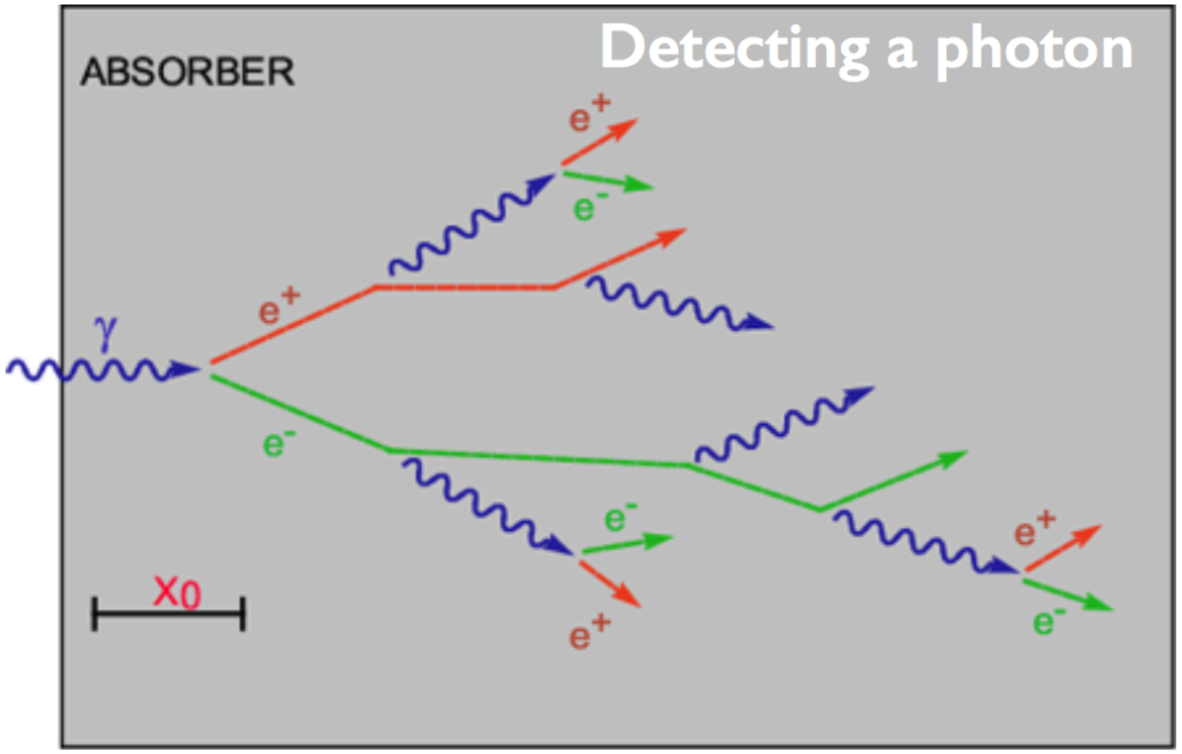

$$\left(\frac{dE}{dx}(E_c)\right)_{ionization} = \left(\frac{dE}{dx}(E_c)\right)_{bremsstrahlung}$$

$$\text{For } Z > 12,\ E_c = \frac{550}{Z}\ \text{MeV}$$

$$\text{In copper } E_c(e) \simeq 20\text{MeV},\ E_c(\mu) \simeq 1\text{TeV},$$

# E.M. Calorimetry

- At high energies electrons lose energies via bremsstrahlung
- The emitted photon has large energy and produces electron-positron pairs
- This creates what is called an electromagnetic shower




Characteristic distance after which the electron loses 1/e of the energy via bremsstrahlung

$$X_0 = \frac{716.4A}{Z(Z+1)ln(287/\sqrt{Z})} gcm^{-2}$$

9/7 of $X_0$ is also the mean three path for pair production by high energy photon

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

# Hadron Showers

- When hadrons interact with matter, in addition to electromagnetic interactions (if they are charged), they have nuclear interaction
- This creates hadronic showers $h + N \to \pi^+\pi^-\pi^0 + ... + N^*$

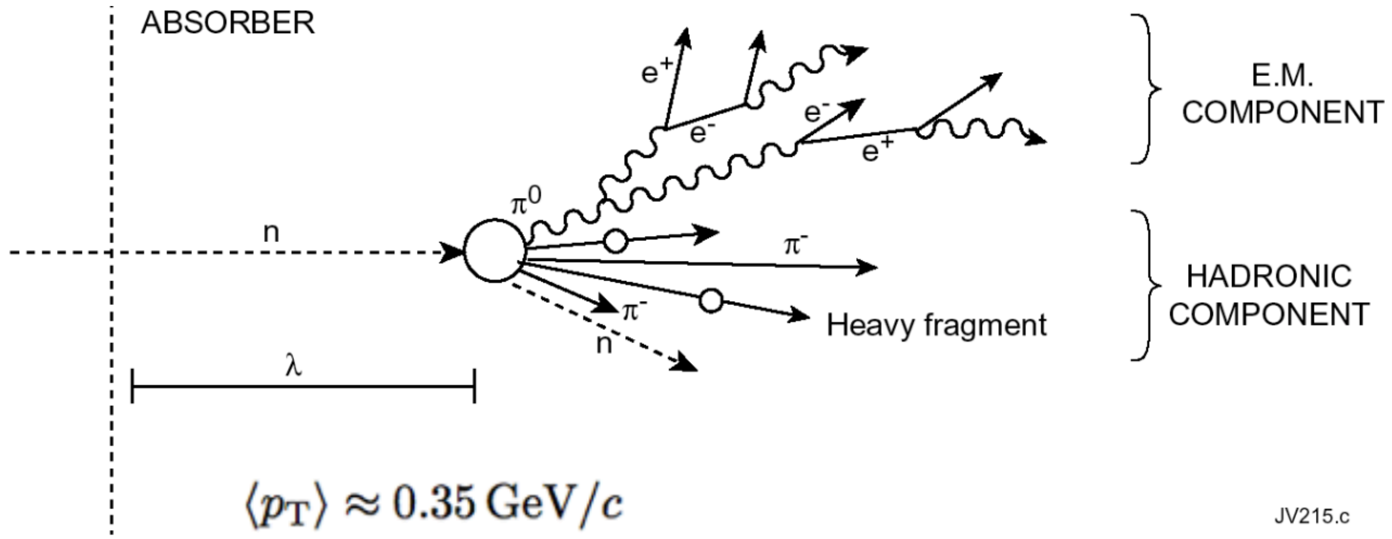
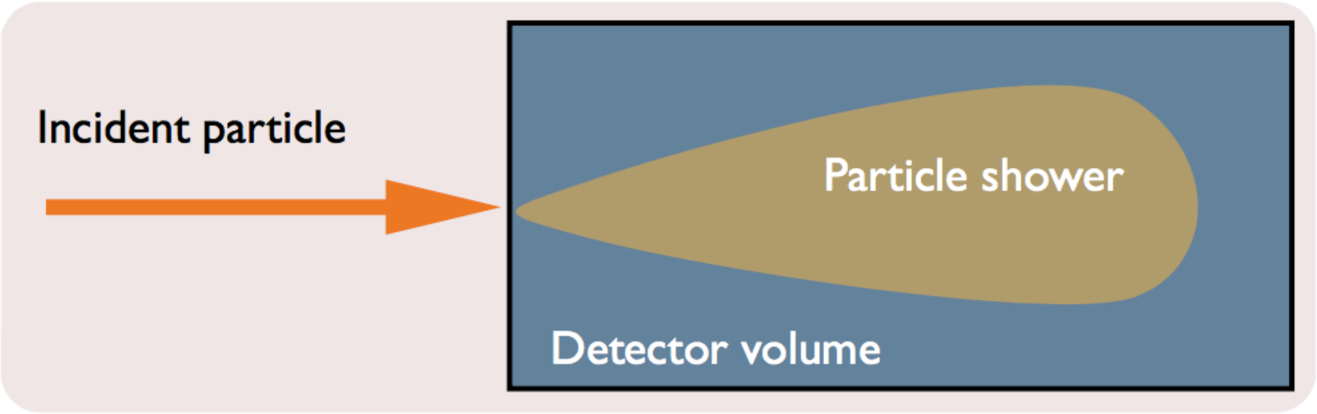



Figure 12: Schematic of development of hadronic showers.

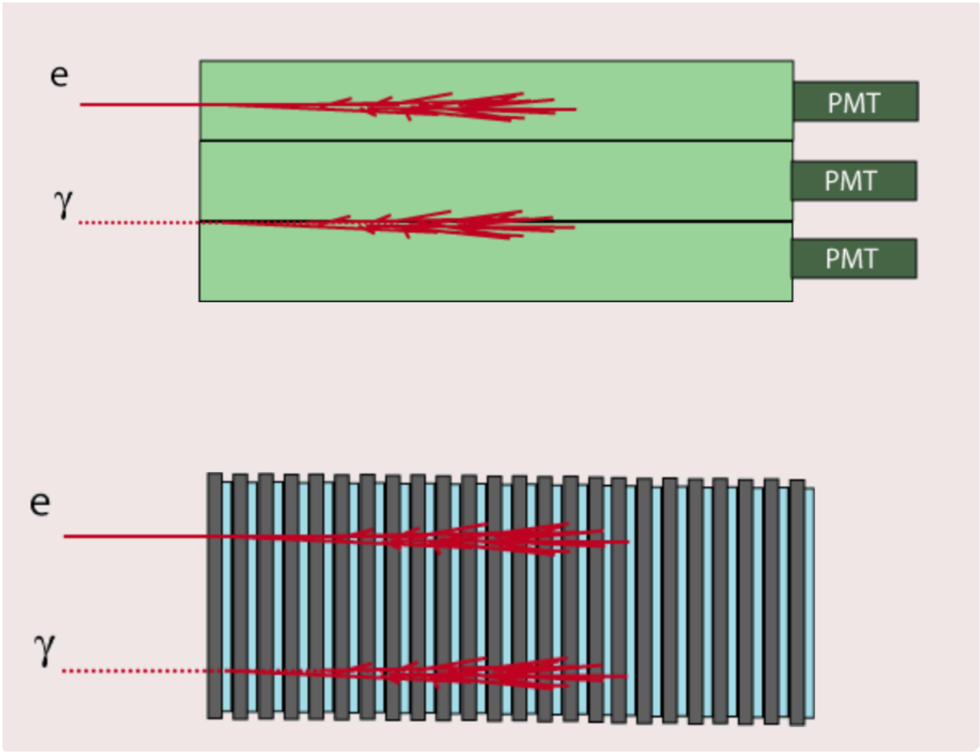
- $Nuclear\ Interaction$ length $\lambda_I \simeq 35 g/cm^2 \cdot A^{1/3}$
- $N(x) = N_0 e^{x/\lambda_I}$
- $\lambda_I \gg X_0$ which implies that hadron calorimeters are much larger than electromagnetic calorimeters

# Calorimetry

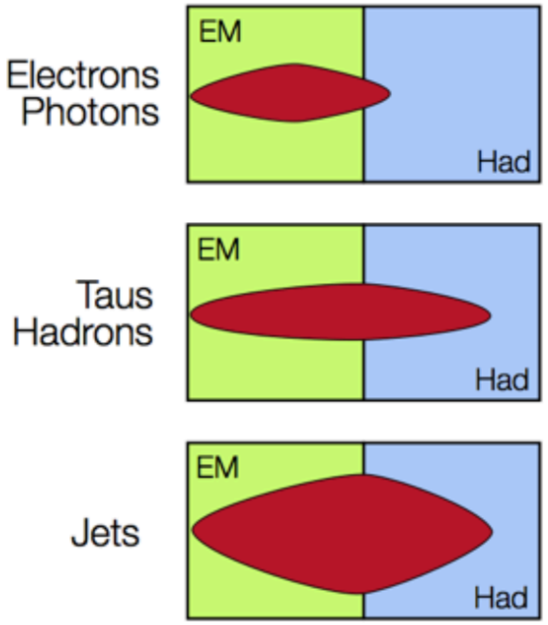



- Calorimeters measure the energy of particle by absorption
- It is a destructive measurement, i.e. the particle energy is deposited in the calorimeter
- There are two types of calorimeters:
  - Electromagnetic calorimeters
  - Hadron calorimeters
- Calorimeters are used for energy measurement and particle identification

# Calorimetry



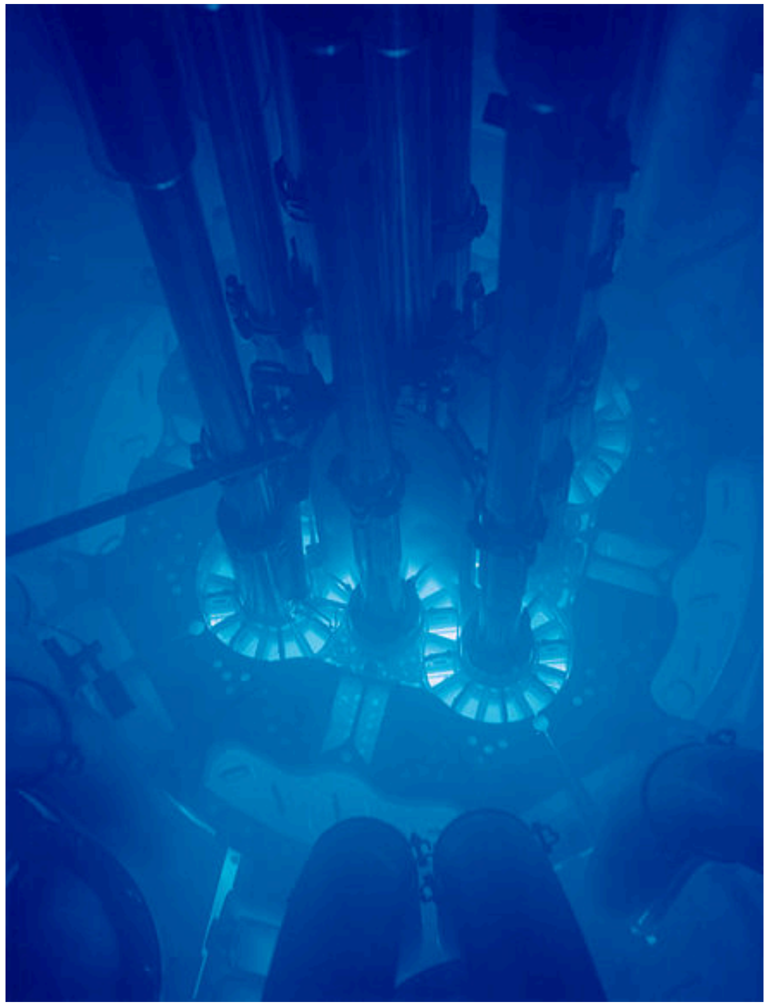

- Homogeneous:
  - total absorption calorimeters, better energy resolution
- Sampling:
  - Sandwich of active and passive material, more compact



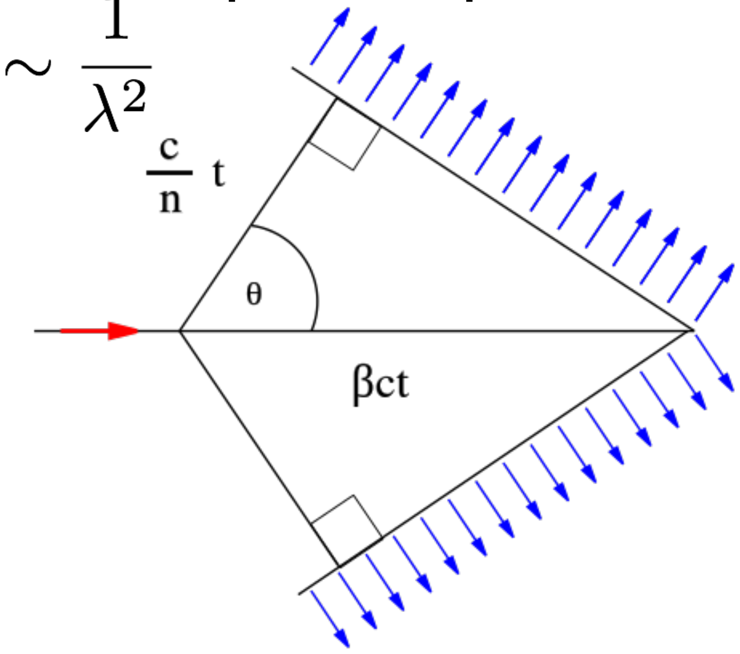

- Electron and photon showers mostly contained in the em calorimeter
- For hadrons/jets the showers is partially in the em calorimeter and partially in the hadron calorimeter
- Shower profile used for particle identification

# Cherenkov Radiation

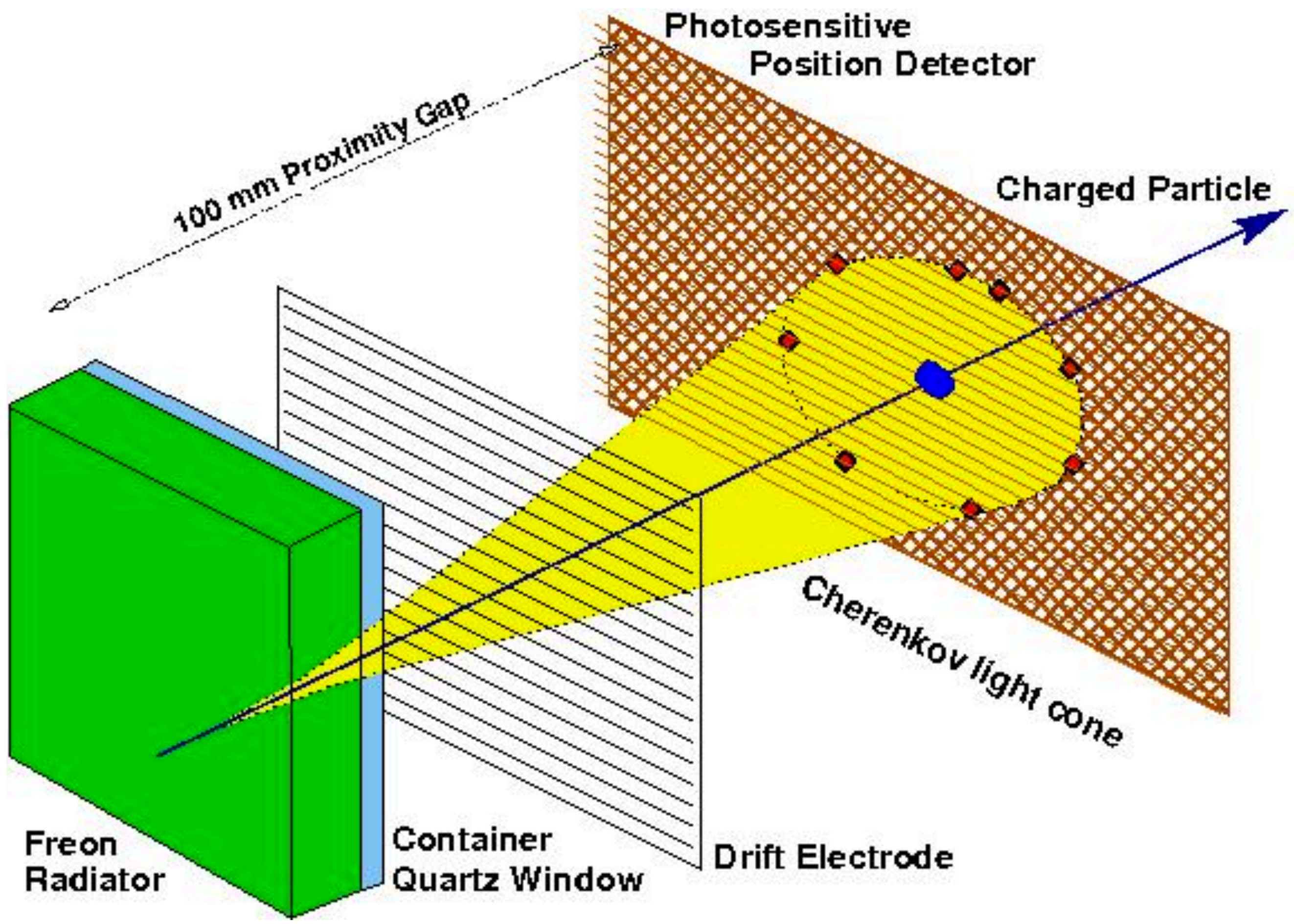
- When a particle passes through a medium exceeding the speed of light in the medium c/n (n is the refractive index) Cherenkov radiation is emitted
- Analogous to the sonic boom of an airplane exceeding the sound speed
- The angle of light emission depends on beta, $\cos\theta = \frac{1}{n\beta}$
- There is a velocity threshold for emitting Cherenkov light $v \geq \frac{c}{n} \rightarrow \beta \geq \frac{1}{n}$



- Energy loss by Cherenkov radiation very small w.r.t. ionization (< 1%)
- Number of emitted photon per wavelength $\sim \frac{1}{\lambda^2}$

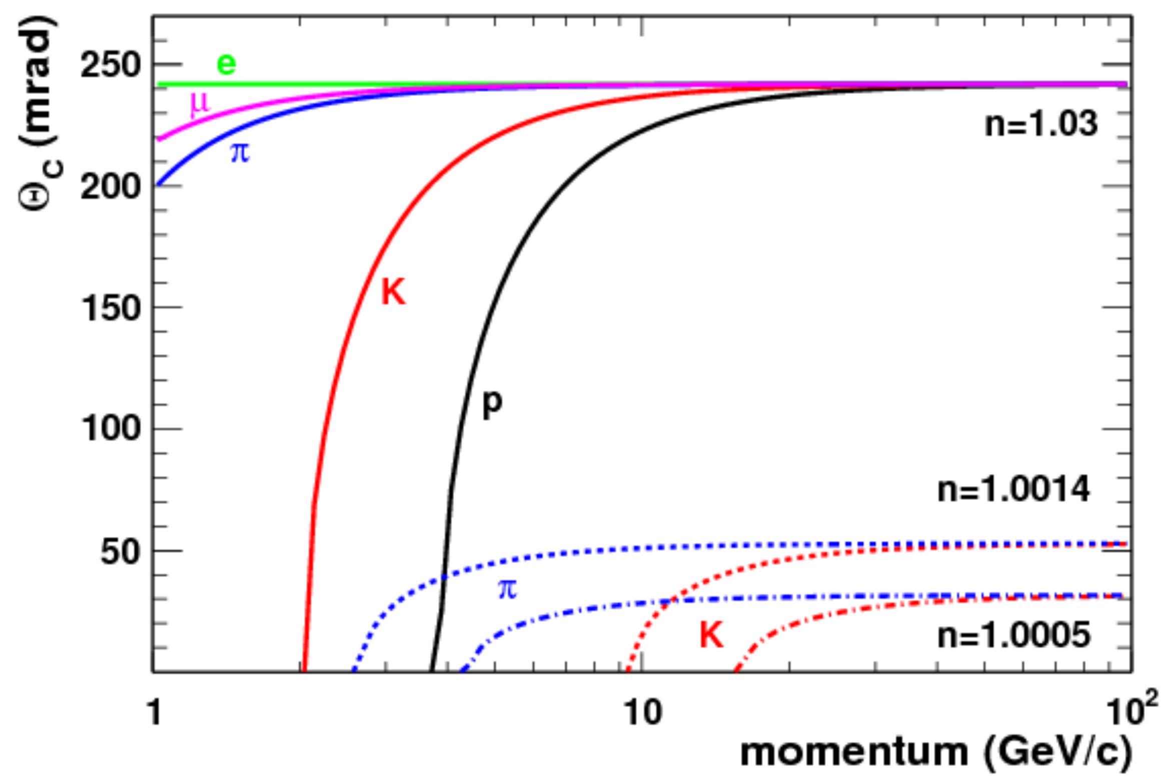


# Cherenkov Detectors



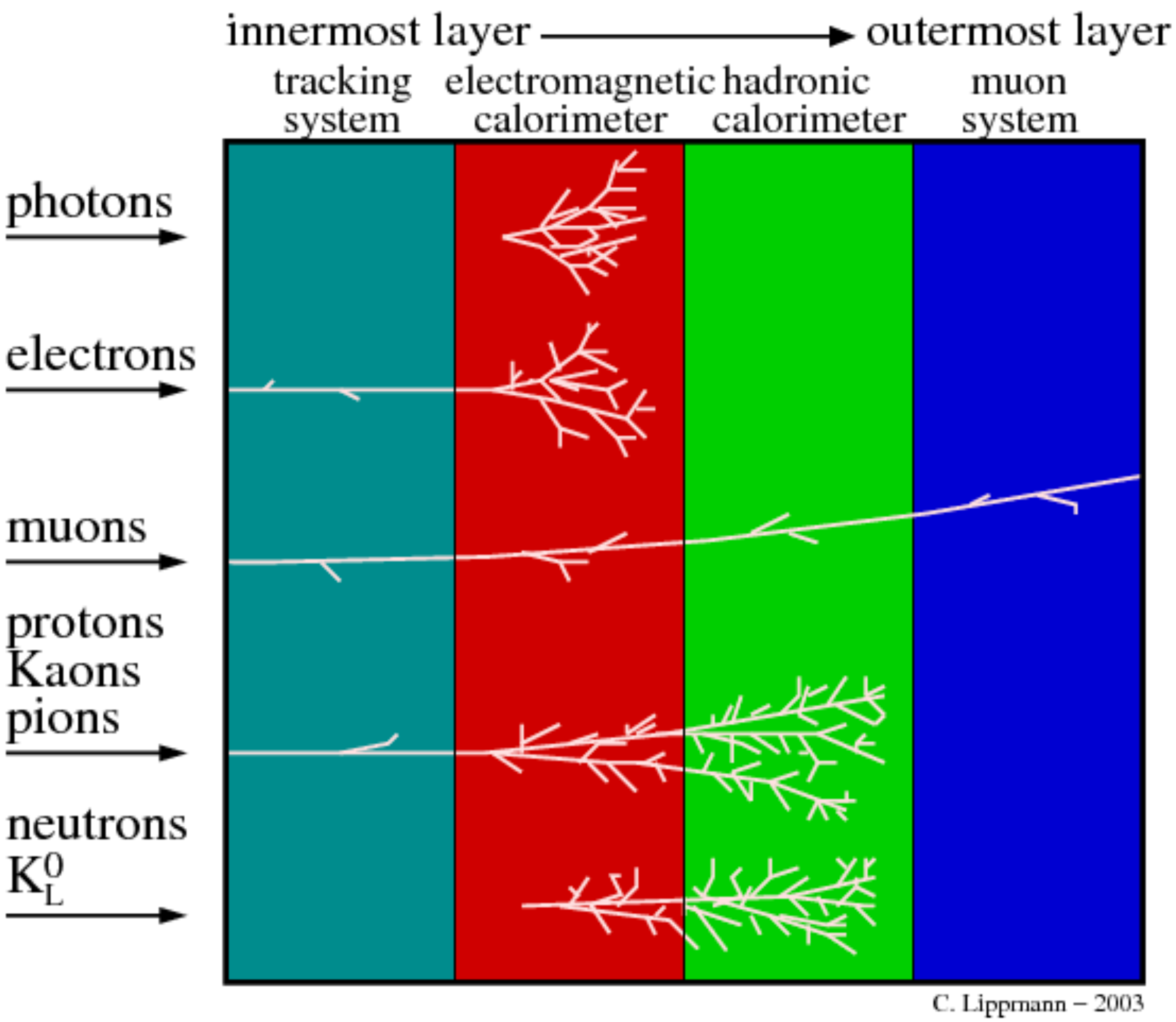

Picture from http://www.iss.infn.it/webg3/cebaf/hadron.html

https://inspirehep.net/record/884672/plots



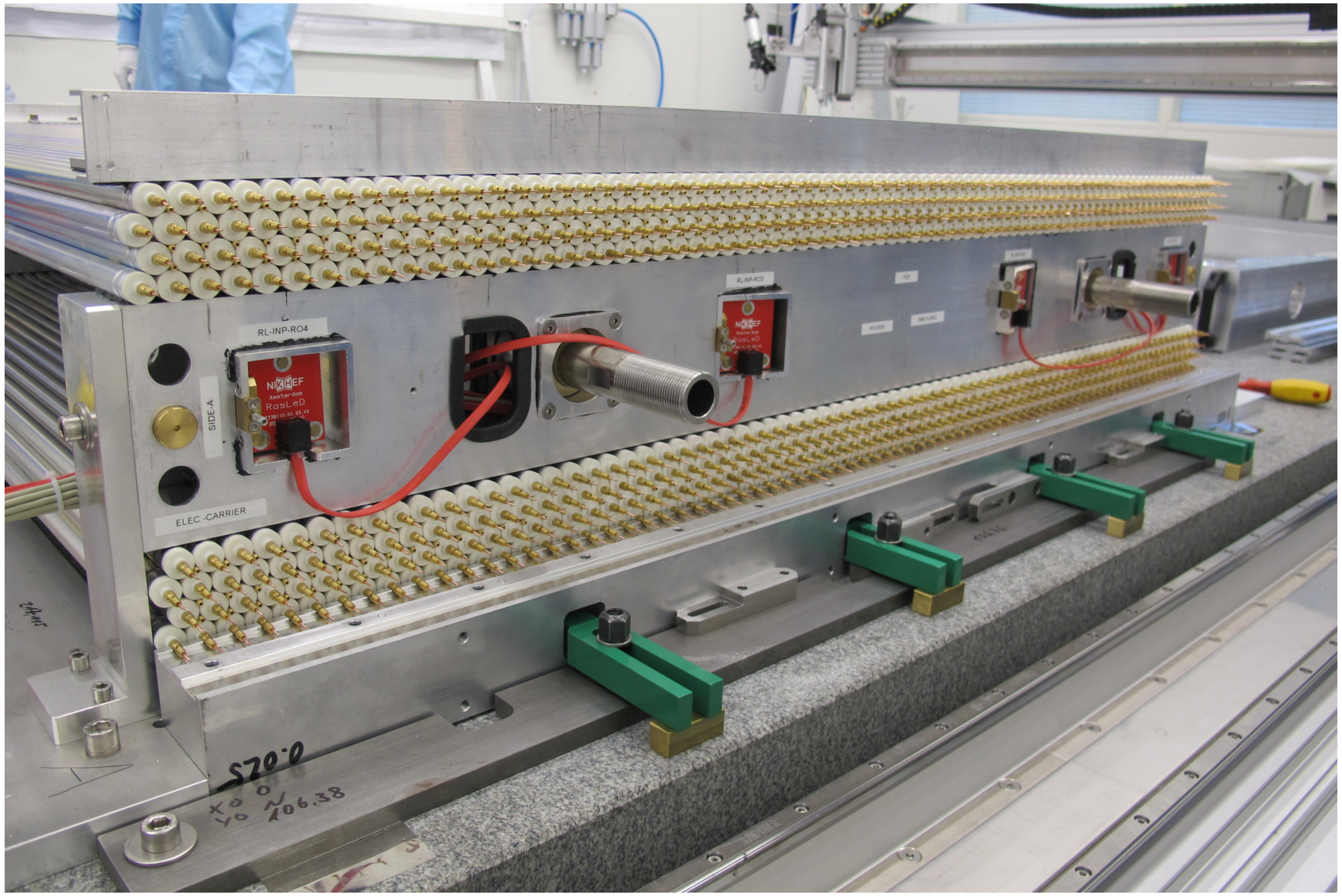

- The Cherenkov light emitted is collected by PMTs
- The circles produced allow to measure the Cherenkov angle $\cos\theta = \dfrac{1}{n\beta}$
- By independently measuring the momentum we can use the RICH detector for particle identification

# Particle Identification




- Particle identification refers to associate the particle identity (photon, electron, muon, kaon, …) to a track and/or energy deposit
- The innermost layer consists of tracking system to measure momentum of charged particles
- Then there is the em calorimeter, that measures em shower
- Then the hadron calorimeter
- Only muons pass through all layers and reach the muon detector (often iron/lead walls are placed between the calorimeter and the muon detector)

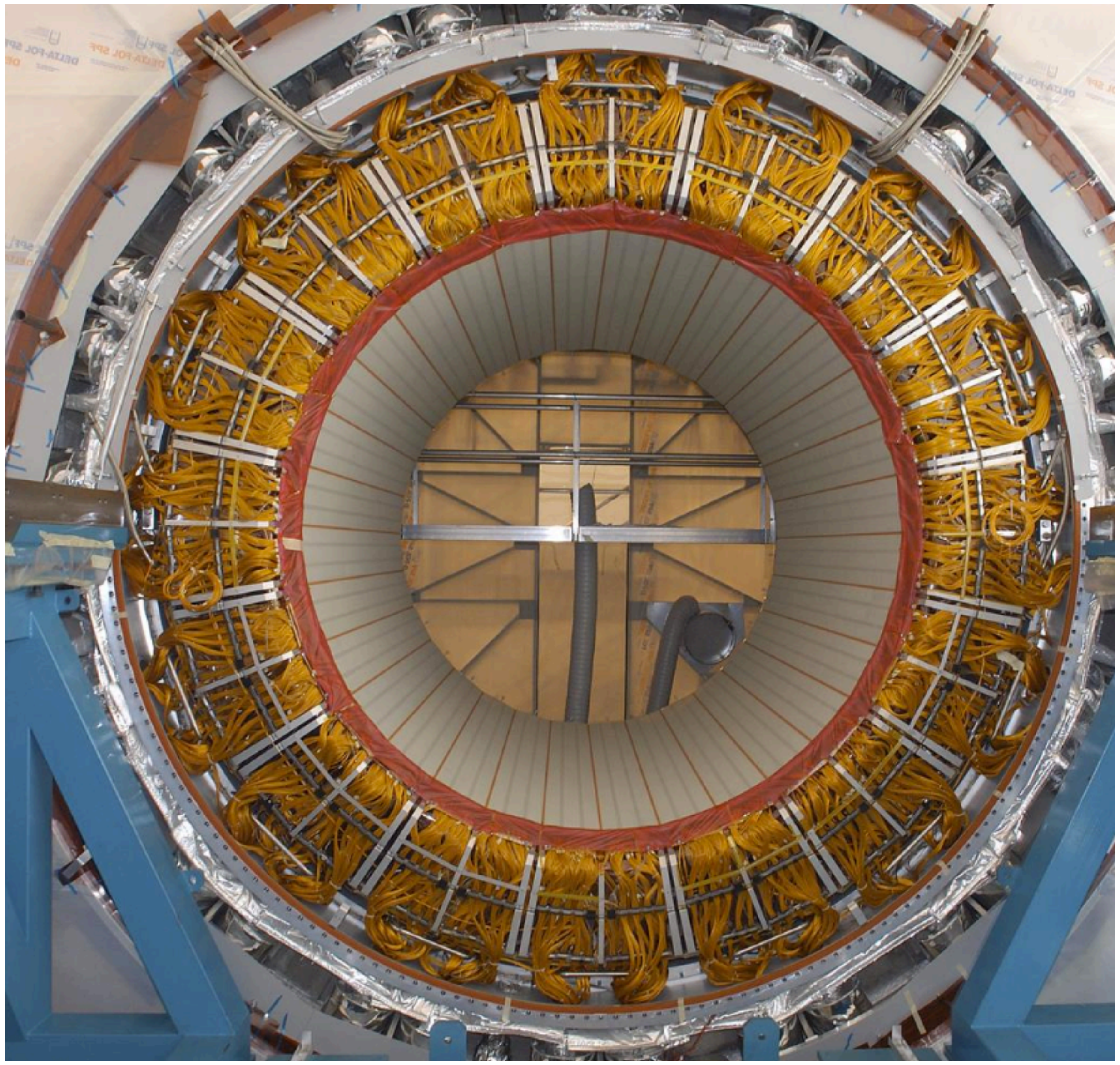
# Pictures

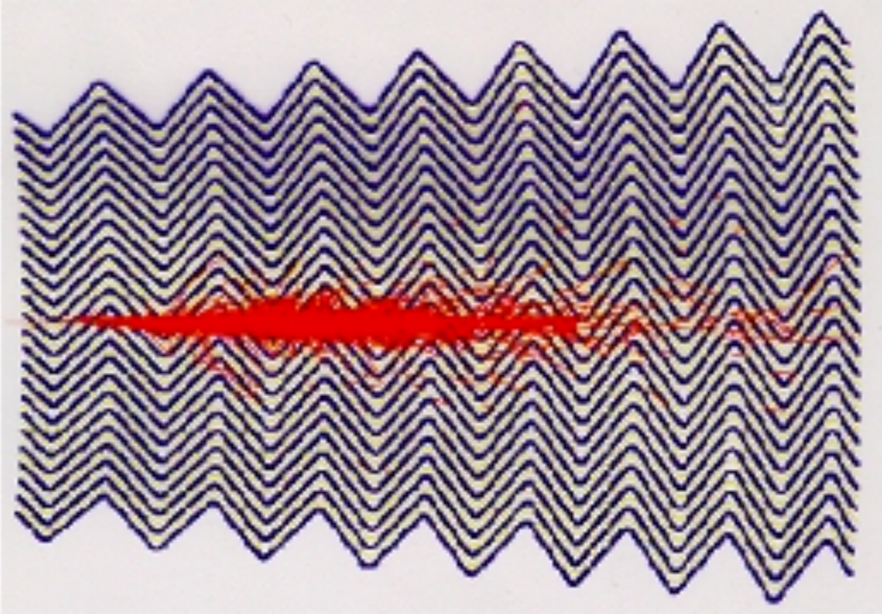


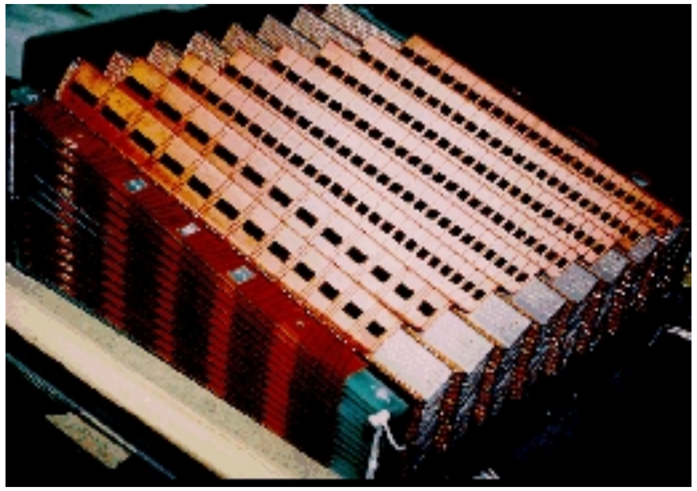
Drift chambers ATALS


Vertex Locator LHCb

# Pictures

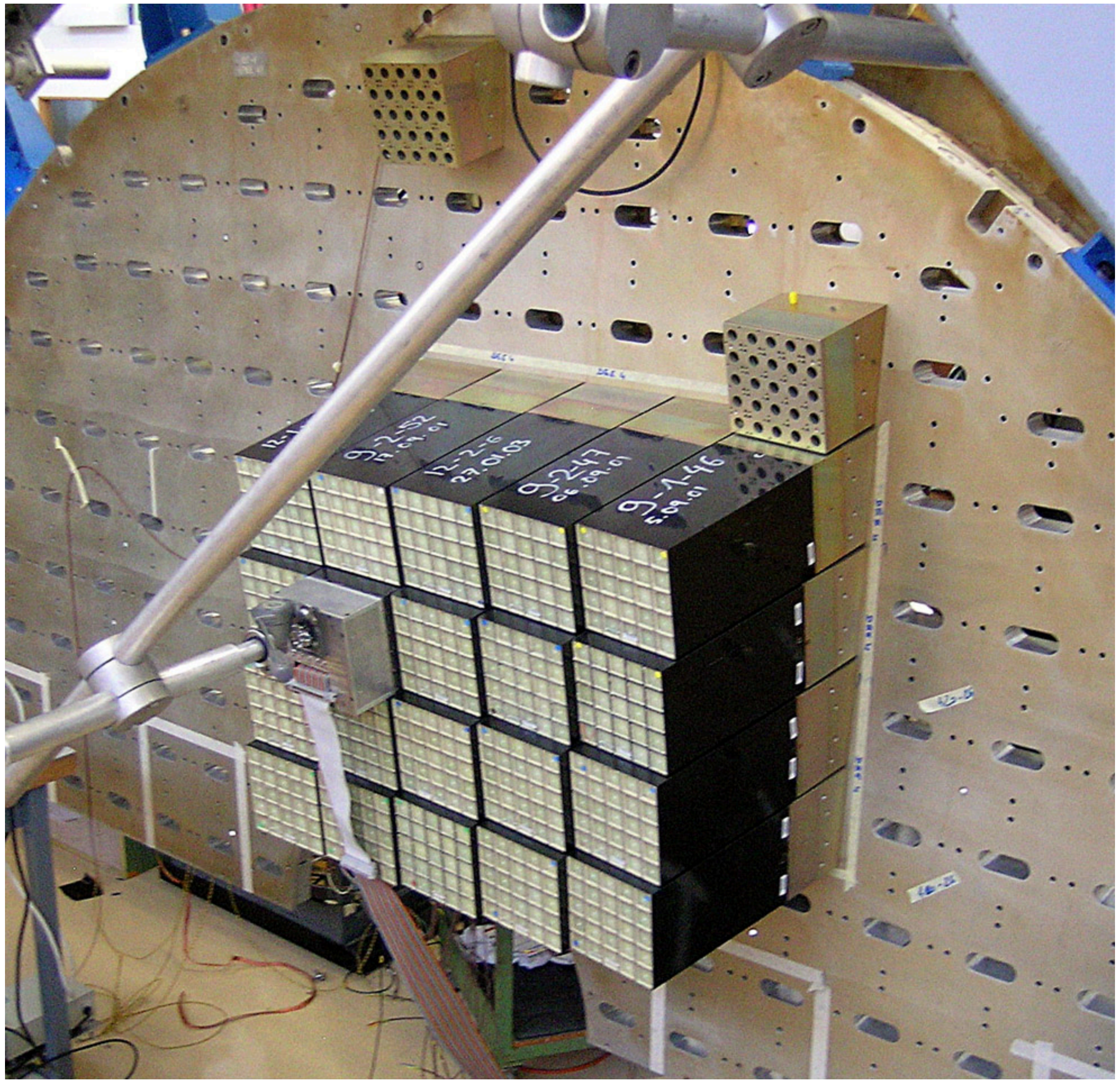


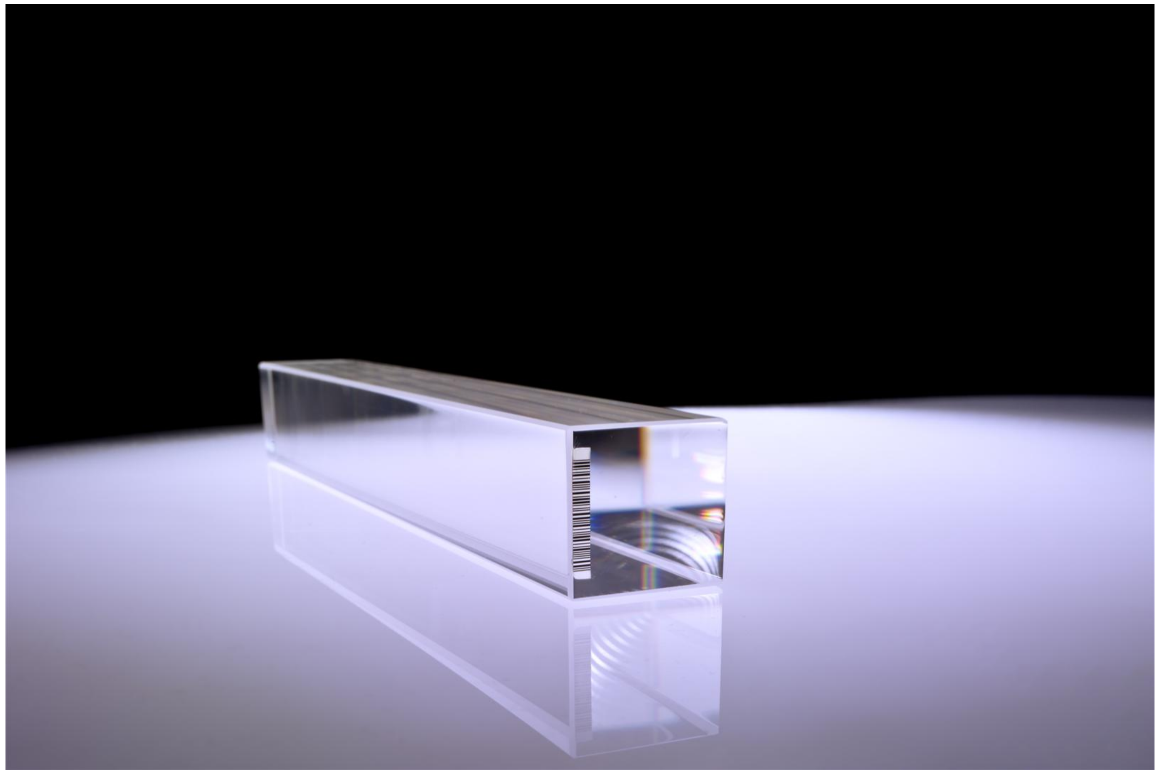




ATALS LAr calorimeter

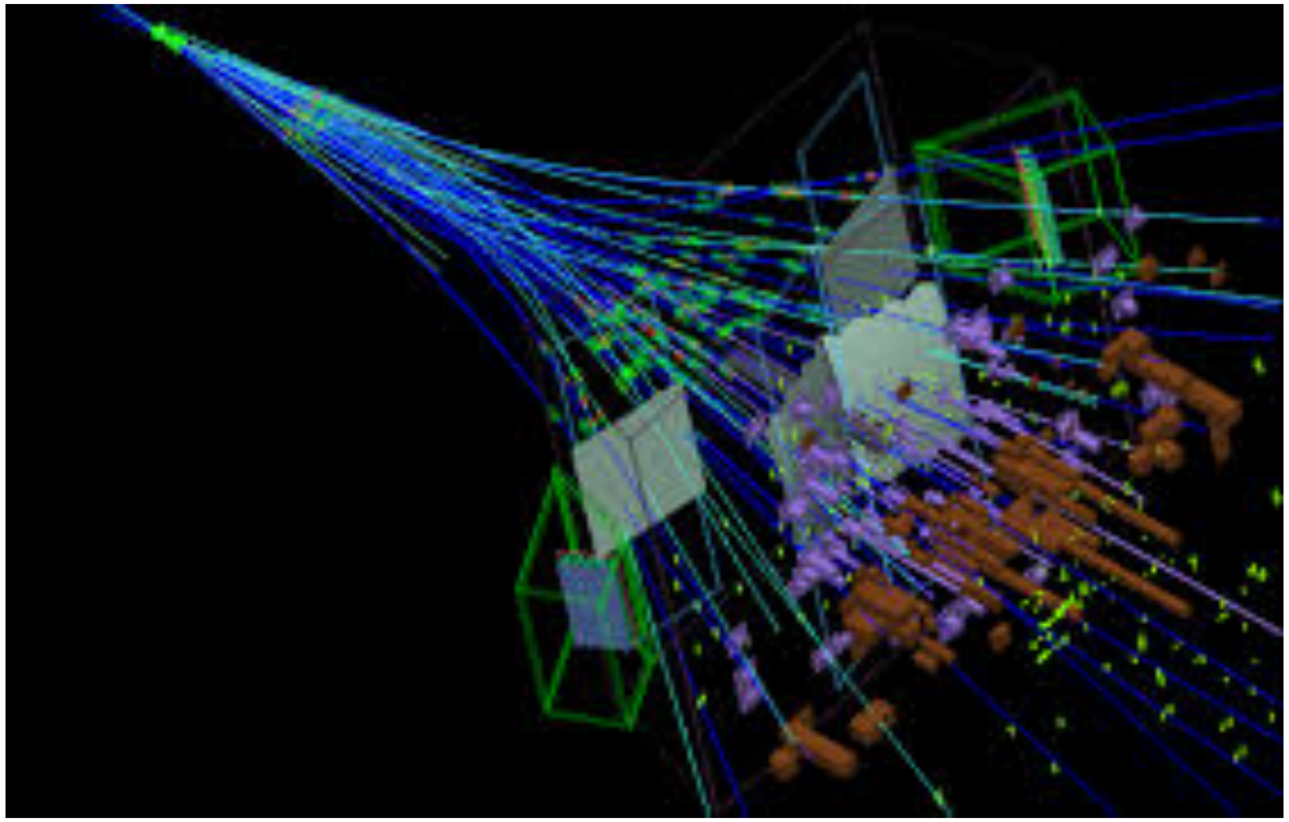
# Pictures



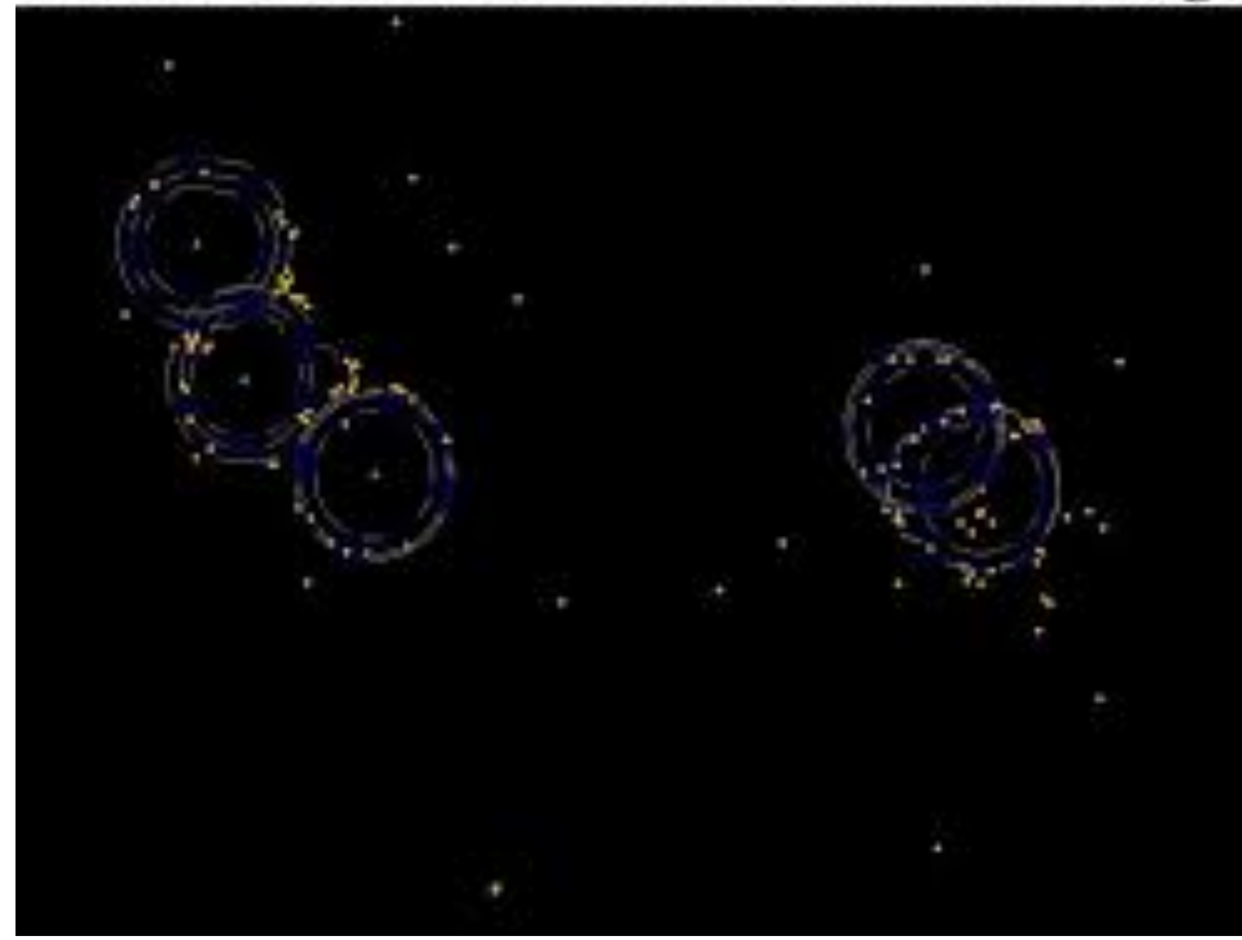


CMS lead tungstate crystals ECAL

# Pictures



RICH2 HPD Panels with Pixels and CK Rings



RICH LHCb

# References

I took inspiration, formulas and pictures from:

- (http://pdg.lbl.gov/2006/reviews/passagerpp.pdf)
- The Physics of Particle Detectors (Erika Garutti - DESY)

http://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/Lectures_SS2012.htm

- Olya Igonkina, Niels van Bakel - Particle Detection Course - NIKHEF