BASIC PHYSICS OF RADIATION DETECTORS

- Interactions of particles with matter
- Some basics of detectors

Alison Lister
University of British Columbia

Interactions of particles with matter

- Introduction
- Heavy charged particles
- Electrons and positrons
- Photons
- Electromagnetic showers
- Strong interactions of hadrons

Suggested references:

- W. Leo, Techniques for Nuclear and Particle Physics Experiments
- The particle Detector Brief Book http://rkb.home.cern.ch/rkb/titleD.html

Basic Types of Detectors

- Ionisation detectors
- Cherenkov detectors
- Scintillation detectors (covered in another talk)
- Semi-conductor detectors (covered in another talk)
- Calorimeters (covered in another talk)

OVERALL INTRODUCTION

Introduction

- Sub-atomic particles involved in particle and nuclear physics are
  - Too small to be observed visually
  - Their detection is based on their interactions with matter
    - In general: based on some energy loss of a particle which is picked up by some reason, thus inferring that a particle crossed through
- The development of particle detectors (as well as accelerators) played a leading role in allowing the development of particle and nuclear physics
    - Geiger counter
    - Cloud chamber (C. T. Wilson, prix Nobel 1927)
    - bubble chamber (D. Glasser, prix Nobel 1960)
    - Wire chamber (G. Chapark, prix Nobel 1992)

See previous lecture

- Applications of particle detectors are everywhere
  - Medicine, biology, condensed matter physics, radiation protection, defence,…
- Detector physics really is multi-disciplinary
  - Particle and nuclear physics
  - Condensed matter physics, thermodynamics, chemistry, electronics, optics,…
  - Engineering (actually making the thing work)

Introduction

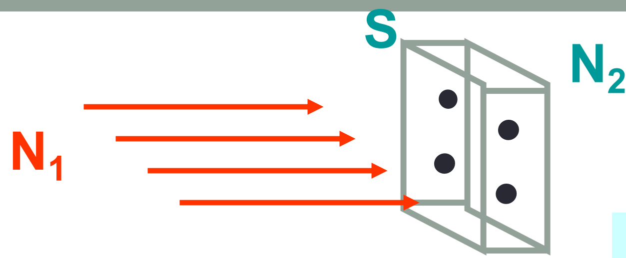
- The main principle of particle detector
  - Measure the energy loss of a particle in a detection medium
- 3 of the 4 forces are relevant
  - EM, strong, weak
- Particles that are sufficiently stable to be detected can be grouped into the interactions they experience

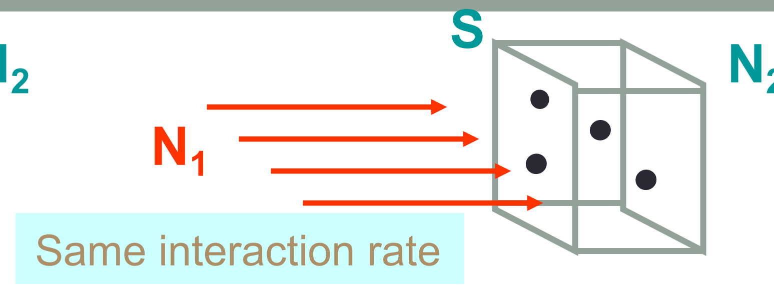
Particle	EM	Weak	Strong
Charged leptons (electron, muon, tau)	✓	✓	
Neutral leptons (neutrinos)		✓	
Charged hadrons (protons, π^+, π^-,...)	✓	✓	✓
Neutral hadrons (neutron, π^0,…)		✓	✓
Photons	✓		

Introduction

- What effects can be induced in a material by a given force?
  - Electromagnetic
    - Interaction between a charged particle and
      - Atomic electrons: excitation, ionisation
      - Charged particles of the nucleus: elastic or inelastic scattering, e^+e^- pair production, bremsstrahlung
    - Interaction between a photon and
      - Atomic electron: photo-electric effect, Compton scattering
      - Particle of the nucleus: e^+e^- pair production
    - Coherent radiation of charged particles
      - Cherenkov radiation and transition radiation
  - Weak
    - Negligible in all cases except for detecting neutrinos
  - Strong
    - Dominant for high energy hadrons and nuclei
- General rule of thumb
  - At low energy: interactions with atomic electrons dominate (excitation, ionisation)
  - At high energy: interactions with nuclei become important

Introduction





- The **interaction probability** (p) depends on the density of the medium (ρ) and the thickness of the medium (d)
  - Take a target with N_2 total particles and a surface S_2
  - Cross section (σ): probability of interaction of an incident particle per unit surface
    - Interaction probability: $p = \sigma N_2 / S_2$
  - Interaction rate: interaction probability of an incident particle times the rate of incident particles
    - $T = \phi S_1 \sigma N_2 / S_2$
      - Flux (ϕ): number of incident particles per unit surface per unit time
      - S_1: surface of the beam
  - Define: $S_b = N_2/S_2 = \rho d$: surface density of the target
    - Number of target particles per unit surface (units: kg/m^2)
  - 2 targets with same surface density will have the same interaction cross section
    - $S_b = (N_A \rho d) / A$

Introduction

- **Mean free path**: λ
  - Mean distance between two successive interactions
  - Calculate the probability that a particle doesn't have an interaction after having traversed a length x in the medium
  - Interaction probability per unit distance
    - $w = p/d = N_A\ (\sigma / A)\ \rho$
  - Interaction probability between *x* et *x+dx*
    - $w\, dx = N_A\ (\sigma / A)\ \rho\ dx$
  - Probability to not have an interaction between *x* et *x+dx*
    - $P(x+dx) = P(x)\ (1 - w\, dx)$
    - $P(x) + P'(x)dx = P(x) - P(x)\ w\, dx$
    - $P'(x) = -wP(x)$
    - $P(x) = e^{-wx}$

$$\lambda = \frac{\int xP(x)dx}{\int P(x)dx} = \frac{1}{w} = \frac{1}{N_A(\sigma/A)\cdot\rho}.$$

which gives us

$$P(x) = e^{-\frac{x}{\lambda}}.$$

HEAVY CHARGED PARTICLES

Heavy charged particles

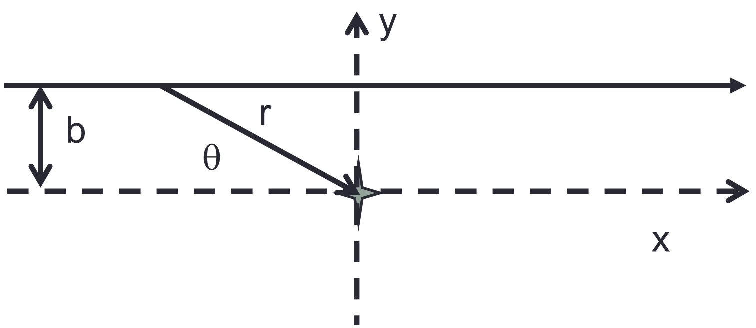
- i.e. all charged particles except electrons et positrons
- At low energy (keV to MeV)
  - Energy loss dominated by EM interactions with atomic electrons
    - Size of an atom ~10^{-10} m
    - Size of a nucleus ~10^{-14} m
  - The interaction results in a transfer of part of the energy of the incident particles into kinetic energy of the atom that will either get ***excited*** (electrons move to higher orbitals) or ***ionised*** (electrons break free)
    - The physics behind this is the same in both cases, just differences in the amount of energy transferred
- The interaction cross section is very small (~10^{-17} cm^2) but the high atomic density ($N_A = 6\ 10^{23}$ g^{-1}) of most materials results in an important energy loss, even for relatively thin layers
  - A 10 MeV proton looses all its energy (on average) in 0.25mm of copper
- Sometimes the freed electrons have enough energy to then ionise an electron from from another atom (so-called δ electrons or δ rays)

Energy loss (*-dE/dx*)

- To describe a material, use the mean energy loss per unit length
  - *-dE/dx*
- Lets try and do a classical calculation of *-dE/dx*
  - EM interactions are described by Coulomb's force
  - Calculate the momentum transferred from an incident particle to an atomic electron

$$I = I_y = \int_{-\infty}^{+\infty} F_y dt = -\int_{-\infty}^{+\infty} \frac{ze^2}{4\pi\varepsilon_0} \frac{\sin\theta}{r^2} \frac{dx}{v} = \int_{-\infty}^{+\infty} \frac{ze^2}{4\pi\varepsilon_0} \frac{b}{vr^3} dx = \int_{-\infty}^{+\infty} \frac{ze^2}{4\pi\varepsilon_0} \frac{b}{v(x^2+b^2)^{3/2}} dx = -\frac{ze^2}{2\pi\varepsilon_0 vb}$$

  - Where *z, v, b* are: the charge, velocity and impact parameter of the incident particle



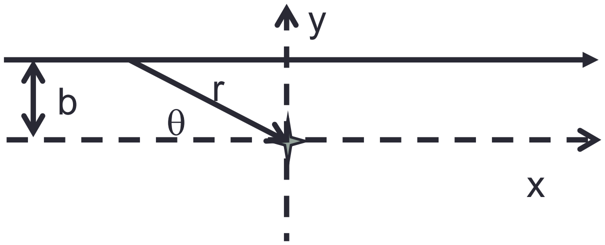
  - The energy transferred to the electron (in the non-relativistic limit)

$$t_e = \frac{I^2}{2m_e} = \frac{z^2 e^4}{8\pi^2 \varepsilon_0^2 v^2 b^2 m_e}$$

Energy loss

- For a uniform electron distribution
  - The number of collisions with an impact parameter between *b* and *b*+*db* in a thickness *dx* of the material is

$$N_e = 2\pi b \cdot db \cdot dx \cdot \rho \cdot (N_A / A) \cdot Z$$



  - Which results in an energy transfer

$$\boldsymbol{dT_e = N_e t_e = \frac{z^2 e^4 Z}{4\pi\varepsilon_0^2 v^2 b m_e} (\rho \cdot N_A / A) \cdot db \cdot dx}$$

  - The energy loss per unit length will thus be

$$-\frac{dE}{dx} = \int_{b_{\min}}^{b_{\max}} dT_e = \frac{Zz^2 e^4}{4\pi\varepsilon_0^2 v^2 m_e} (\rho \cdot N_A / A) \int_{b_{\min}}^{b_{\max}} \frac{db}{b} = \frac{Zz^2 e^4}{4\pi\varepsilon_0^2 v^2 m_e} (\rho \cdot N_A / A) \ln\left(\frac{b_{\max}}{b_{\min}}\right).$$

Energy loss

- Because of the approximations made here we will get an infinite result when b_{min}= 0 and b_{max} = infinite
- We can solve this by putting limits to the integration region based on physics arguments
  - We consider the mass of the incident particle to be >> m_e
    - The maximum change of the speed of the electron will be 2v
    - The energy acquired by the electron cannot exceed $$t_{e,\max} = \frac{1}{2} m_e (2v)^2 = 2 m_e v^2$$
    - Which corresponds to a minimum to the impact parameter $$b_{\min} = \frac{ze^2}{4\pi\varepsilon_0 v^2 m_e}$$
  - The minimum energy change needs to e enough to excite the atom: i.e. be above the ionisation constant *I*

$$t_{e,\min} = I \quad \text{d'où} \quad b_{\max} = \frac{ze^2}{2\pi\varepsilon_0 \sqrt{2 m_e v^2 I}}$$

- We then get

$$-\frac{dE}{dx} = \frac{Zz^2 e^4}{8\pi\varepsilon_0^2 v^2 m_e} (\rho \cdot N_A / A) \ln\left(\frac{2 m_e v^2}{I}\right) = \frac{2\pi Z z^2 r_e^2 m_e c^4}{v^2} (\rho \cdot N_A / A) \ln\left(\frac{2 m_e v^2}{I}\right)$$

  - Where r_e is the classical electron radius

Energy loss: Bethe-Bloch

- Bethe and Bloch did the full QM calculation and got

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

  - δ: the correction for charge density effects
  - W_{max}: the maximum energy transferred in a collision

$$W_{\max} = \frac{2m_e c^2\beta^2\gamma^2}{1 + 2\gamma\frac{m_e}{M} + \left(\frac{m_e}{M}\right)^2} \approx 2m_e v^2\gamma^2 \quad \text{pour } M >> 2\gamma m_e$$

- Thus

$$-\frac{dE}{dx} \approx \frac{4\pi Z z^2 r_e^2 m_e c^2}{\beta^2}(\rho \cdot N_A / A)\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

$$= \left(4\pi m_e c^2 r_e^2\right)\frac{n_e z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

$$= \frac{1}{m_e c^2}\frac{e^4}{4\pi\varepsilon_0^2}\frac{n_e z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right]$$

  - Where n_e is the atomic electron density

Bethe-Bloch

- The ionisation constant (*I*) groups together the global properties of atoms
  - Excitation levels and associated cross sections
  - Difficult to calculate
    - Measured experimentally for different materials
    - Parameterised as a function of the number of electrons (Z)

$$I/Z = \begin{cases} 12 + 7/Z & \text{eV} \quad Z < 13 \\ 9.76 + 58.8Z^{-1.19} & \text{eV} \quad Z \geq 13 \end{cases}$$

  - The correction for the charge density (δ) is due to the fact that the electric field of the incident particle polarises the atoms close to its trajectory
    - The polarisation reduces the impact of the electric field of the further away electrons (like a screening effect) which reduces the energy loss
      - *i.e.* $\delta > 0$
    - The effect becomes larger if the energy of the incident particle increases (longer range electric field) or the density of material increases

Heavy charged particles

- To simplify we can use $K = 4\pi N_A r_e^2 m_e c^2 \approx 0.307075\ \mathrm{MeV \cdot g^{-1} \cdot cm^2}$

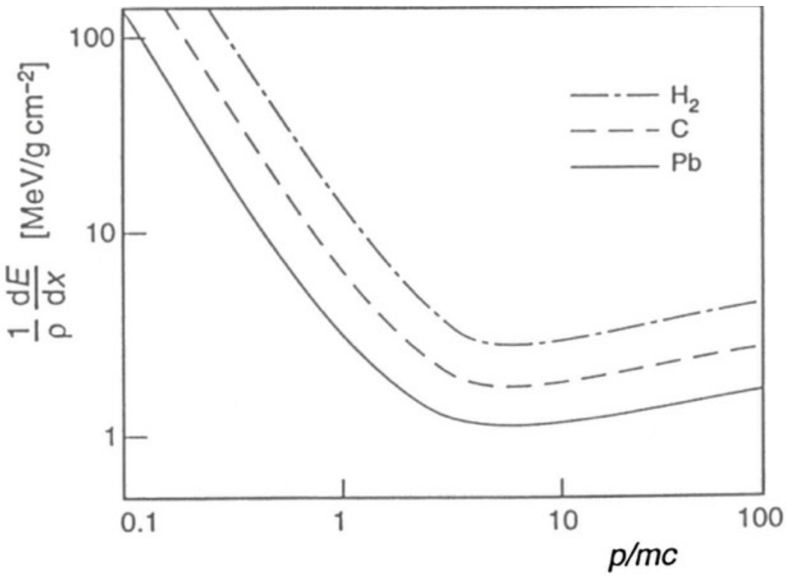
  - We can express *-dE/dx* in units of energy divided by the surface density

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

    - Proportional to z^2
      - An α particle looses 4 time more energy than a proton for the same speed in the same medium
      - Proportional to Z/A
      - Z/A ~1/2 pour for most medium except for hydrogen

Energy dependence of-*dE/dx*

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

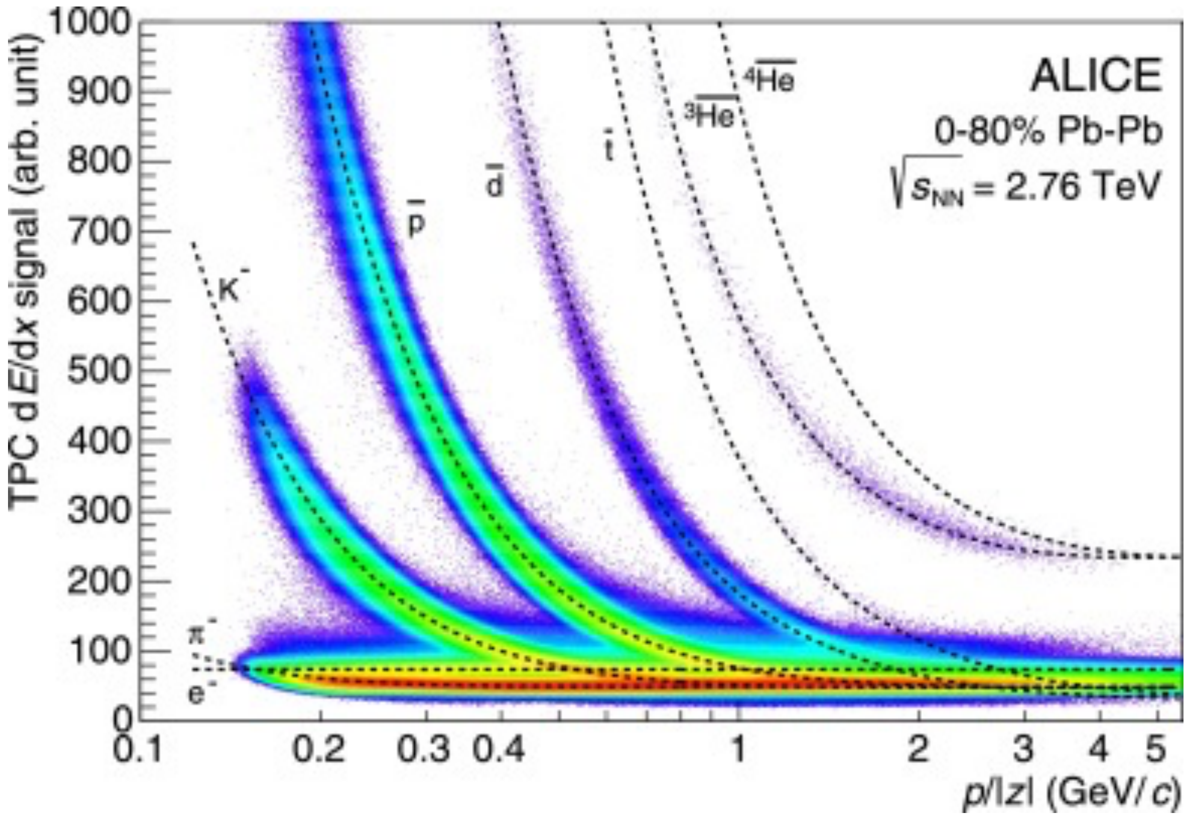


- For non-relativistic particles: $1/\beta^2$ term dominates
  - The particle spends longer closer to the electrons -> the momentum they gain is larger
- This decrease continues to a minimum at $p/mc = \beta\gamma \sim 3 - 3.5$ (when the particle becomes relativistic)
  - The particles at this minimum are called 'minimally isonising particles'
  - The *-dE/dx* minimum is constant for all particles with the same charge, in the same medium
    - Moreover it's almost constant (1-2 MeV/g/cm^2) for most materials
- At high energies ($\beta \sim 1$): *-dE/dx* increases as log $\beta\gamma$, compensated by the density correction
- In a given medium, each particle has a different curve
  - This can be used to identify the type of particle

Energy dependence of-*dE/dx*

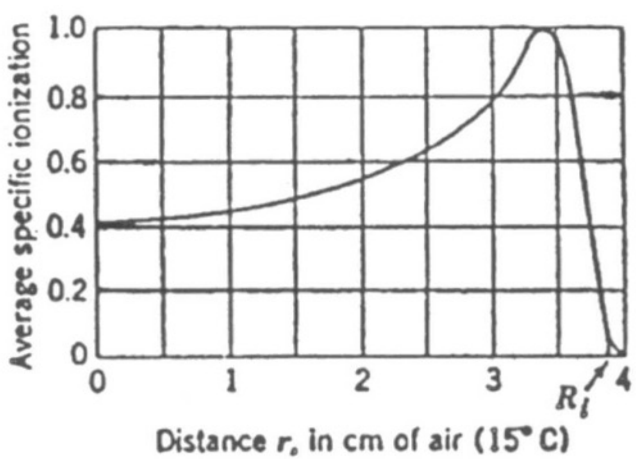
$$-\frac{dE}{\rho dx} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}\right].$$

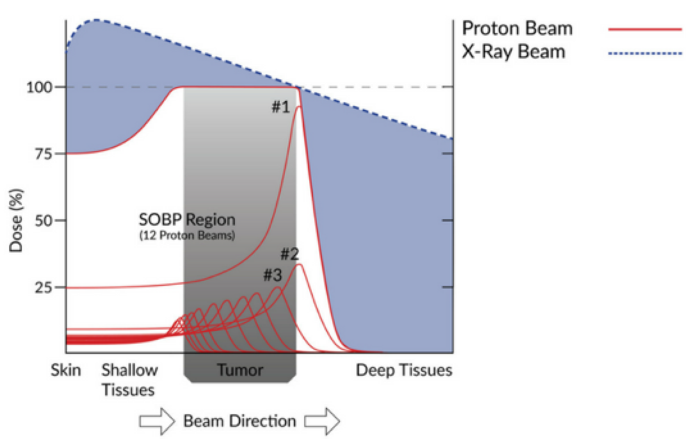
Energy loss for different types of particles in ALICE's TPC (Time Projection Chamber)



Bragg Curve

- When entering a dense medium: a particle looses energy, thus slowing down, until it looses all its kinetic energy and stops
  - The slower the particle, the larger the *-dE/dx*
- The relationship between *-dE/dx* and the distance travelled in the medium is called the Bragg curve
- The curve increases to a maximum
  - The depth at which the particle gets absorbed is the Bragg peak
- This Bragg peak is exploited in nuclear medicine for radiation treatment in order to minimise the damage to healthy tissue in front of the tumor





Validity of Bethe-Block formula

- Precision of a few % for heavy charged particles in the range from a few MeV to hundreds of GeV
  - At very high energy (TeV): the energy loss by radiation becomes important so additional terms are needed
  - At very low energy (< few MeV): when the speed of particles is comparable to the speed of atomic electrons the formula breaks down completely
- The energy loss process is a statistical (probabilistic) process
  - If the target if very thin: particle by particle variations in -dE/dx become important
    - Results in an asymmetric distribution with a large tail (at high values)
    - These fluctuations are in general linked to *δ electrons (which are discreet)*
    - Can be roughly parametrised by a Landau distribution

$$L(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left\{ -\frac{1}{2}(\lambda + e^{-\lambda}) \right\} \quad \text{avec} \quad \lambda = \frac{\Delta E - \Delta E^W}{\xi}$$

ΔE : la perte d'énergie dans une épaisseur x

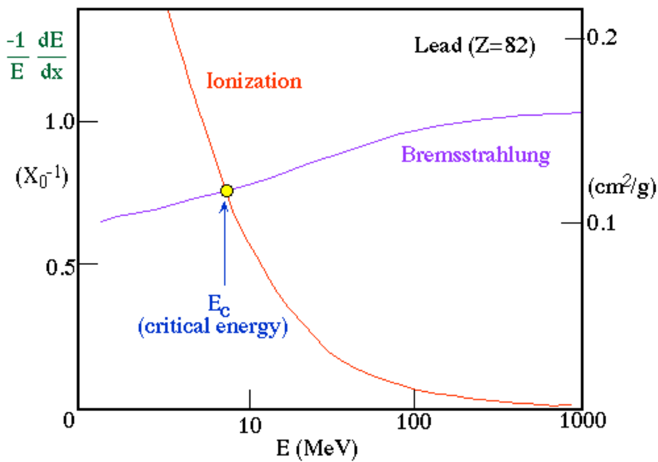
ΔE^w : la perte d'énergie le plus probable dans une épaisseur x

$$\xi = 2\pi N_a r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \rho x$$

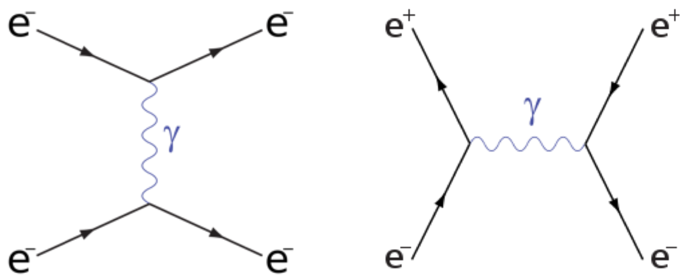
LIGHT CHARGED PARTICLES

Electrons and positions (light charged particles)

- Electrons and positrons are light: Need to modify the Bethe-Block formula
  - Masses of incident particles = masses of target particles
    - For electrons: it's the same particle
  - Only need a single interaction to significantly change the direction of the incident electron
    - Makes the trajectory more sinuous and harder to predict
  - Energy loss by radiation (Bremsstrahlung) becomes important
    - $dE/dx_{tot} = dE/dx_{radiation} + dE/dx_{collision}$
    - For energies up to a few MeV: small fraction
    - For a few tens of MeV: energy losses are comparable
    - Above that: Bremsstrahlung dominates



Electrons and positrons



- Need to modify Bethe-Block formula
- Basic interactions
  - Moller scattering ($e^-e^- \rightarrow e^-e^-$)
  - Bhabha scattering ($e^+e^- \rightarrow e^+e^-$)
- Using the cross sections for these processes, we get

$$-\frac{dE}{\rho dx} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\ln\left(\frac{m_e c^2 \tau\sqrt{\tau+1}}{\sqrt{2}I}\right) + \frac{F(\tau)}{2} - \frac{\delta}{2}\right]$$

  - τ is the kinetic energy of the electron (positron) in units of $m_e c^2$
  - $F(\tau)$ is a function that's different for electrons and positrons

Energy loss by radiation (Bremsstrahlung)

- A charged particle looses energy be emission of EM radiation (photon) when its velocity (vector or magnitude) changes
  - Bremsstrahlung: in the electric field of a nucleus
  - Synchrotron radiation: under circular motion
- The radiation emission cross section $d\sigma/dE_\gamma \propto 1/m^2$
  - A semi-classical calculation gives

$$\frac{d\sigma}{dE_\gamma} \propto 4\alpha\, z^2 Z^2 \left(\frac{e^2}{4\pi\varepsilon_0 m^2 c^2}\right)\frac{1}{E_\gamma}$$

  - Below ~100 GeV
    - Only electrons and positrons loose non-negligible energy due to radiation

Energy loss by radiation (Bremsstrahlung)

- The spectrum of the emitted photon depends on $1/E_\gamma$

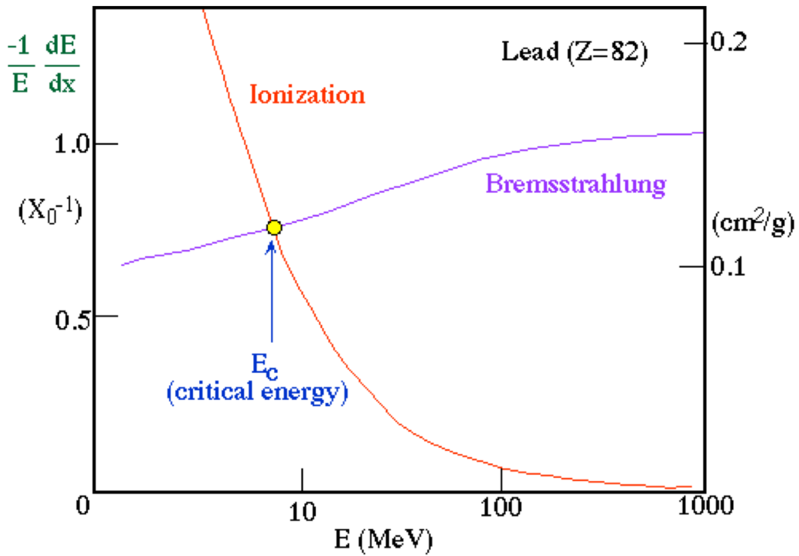
$$-\left.\frac{dE}{dx}\right|_{brem} = \int_0^E E_\gamma p(E_\gamma) dE_\gamma = N_a \frac{\rho}{A} \cdot \int_0^E E_\gamma \frac{d\sigma}{dE_\gamma} dE_\gamma \propto E$$

  - For relativistic particles (energy ~ MeV)

$$-\left.\frac{dE}{dx}\right|_{brem} = 4\alpha N_a \frac{\rho}{A} Z^2 z^2 r_e^2 E \ln\frac{183}{Z^{-1/3}}$$

  - Bremsstrahlung is also emitted in the interaction of the incident electron and the electric field created by the atomic electrons
    - Taken into account by replacing Z^2 by $Z(Z+1)$
  - Energy loss is proportional to E
    - Dominant contribution at high energy
- Critical energy
  - The energy at which the energy loss by radiation equals the energy loss by ionisation

à $E = E_c, \quad -dE/dx|_{brem} = -dE/dx|_{ion}$



Radiation length

- We can describe the energy loss as

$$-\left.\frac{dE}{dx}\right|_{brem} = \frac{E}{X_0}, \quad \text{ou} \quad X_0 = \frac{A}{4\alpha N_a \rho Z(Z+1) r_e^2 \ln \frac{138}{Z^{1/3}}}$$

$$E(x) = E_0 \exp(-x/X_0), \quad \text{donc} \quad E(X_0) = E_0/e$$

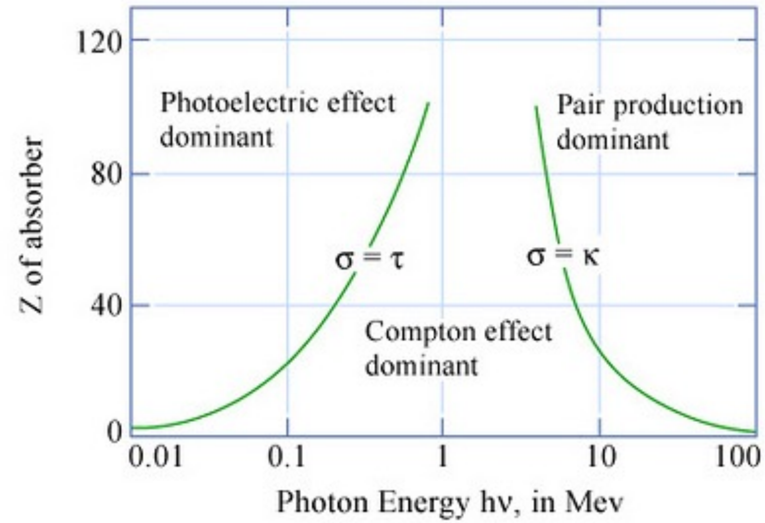
- X_0 is the radiation length
  - After having traversed a distance X_0: On average the electron energy will be reduced by a factor of 1/e because of Bremsstrahlung
  - X_0 is often given in units of surface density (g/cm^2), it is then re-defined as

$$X_0 = \rho \cdot X_0(cm) = \frac{A}{4\alpha N_a Z(Z+1) r_e^2 \ln \frac{138}{Z^{1/3}}} \ \mathrm{g \cdot cm^{-2}}$$

PHOTONS

Photons

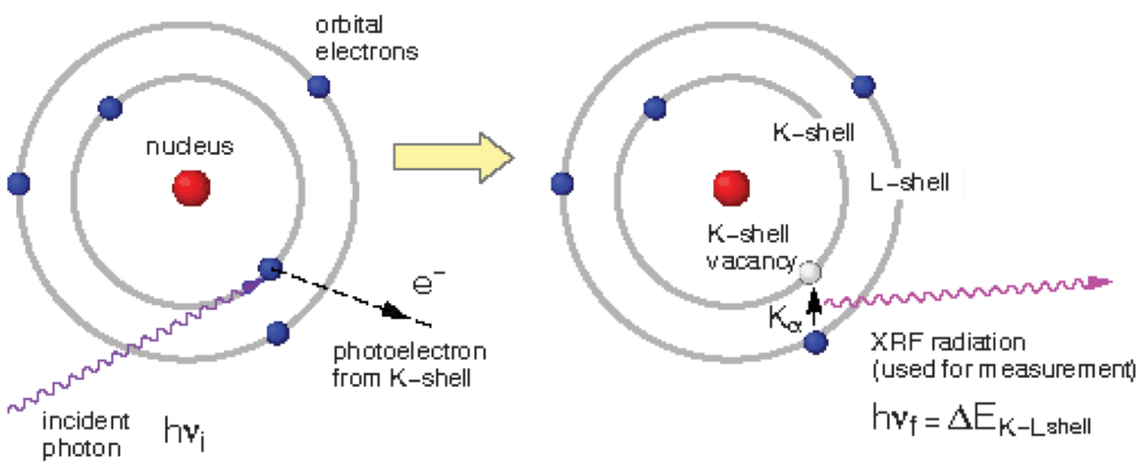
- Photons are detected through interactions with matter that produce charged particles
  - Photoelectric effect
    - Dominant for $E_I < E_\gamma < 100$ keV
  - Compton scattering
    - Dominant for $E_\gamma \sim 1$ MeV
  - e^+e^- pair production
    - Dominant for $E_\gamma >> 1$ MeV



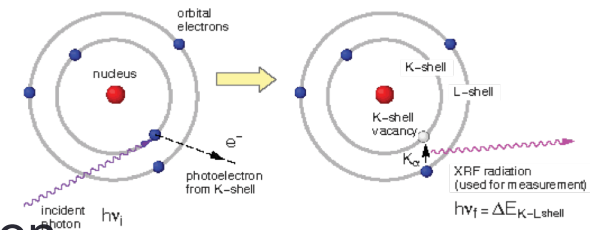
- In all of these processes, the photon is either absorbed of scattered by a large angle
  - A beam of photons will thus keep its energy, but the intensity decreases
    - We talk about attenuation instead of energy loss
  - Attenuation coefficient $\mu = n\sum_i \sigma_i$ where *n* is the nuclear density
  - Interaction probability in a thickness *dx* is $n\sum_i \sigma_i \cdot dx = \mu\, dx$
    - The beam intensity at *x+dx* $I(x+dx) = I(x)(1-\mu dx)$
  - The beam intensity thus decreases exponentially $I(x) = I_0 e^{-\mu x}$

Photoelectric effect

- An atomic electron is freed after having absorbed a photon T_e ª $E_g - B_i$
  - Where B_i is the binding energy of the electron (which depends on the orbital layer: k,l,m)
  - This process ($\gamma + e^- \rightarrow e^-$) is not possible for a free electron
    - Violates momentum conservation
  - If $E_\gamma > B_K$, the cross section is dominated (80%) by the absorption by electrons in layer k (innermost layer) as the proximity to the nucleus allows easier absorption of the recoil energy



Photoelectric effect

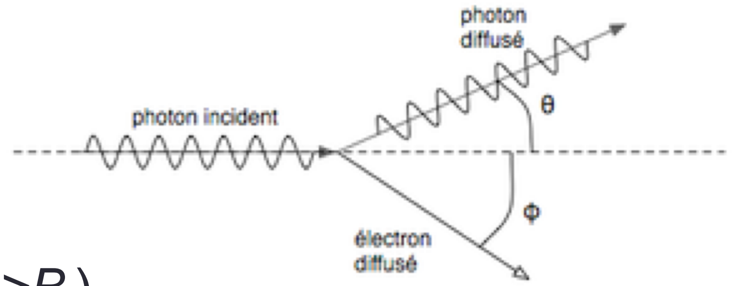


- A non-relativistic calculation gives an approximation

$$\sigma_K = 4\sqrt{2}\alpha^4 Z^5 \left(\frac{m_e c^2}{E_\gamma}\right)^{7/2} \sigma_{Th} \quad \text{où} \quad \sigma_{Th} = \frac{8}{3}\pi r_e^2 = 6.65\cdot 10^{-25}\,\text{cm}^2$$

  - Where σ_{Th} is the classical Thomson scattering cross section (elastic scattering off free electrons)
    - The dependency on Z^5 and $E_\gamma^{-7/2}$ favours the photoelectric effect at low energy and in heavy materials
  - At high energy (in the relativistic limit) the dependency goes as $1/E_\gamma$
- The electron hole left can be filled by electrons from higher orbitals (e.g. L) which results in
  - Either the emission of an X-ray with energy B_K-B_L
  - Or the emission of another electron (Auger electron)
    - If $B_K – B_L > B_L$ we will get the emission of an electron with $E_{Auger} = B_K – 2B_L$

Compton Scattering



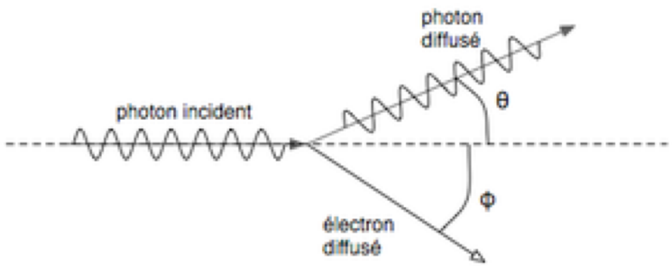
- A photon scatters of a quasi-free electron ($E_\gamma >> B_i$)
- Cross section is given by the Klein-Nishima formula (obtained from QED)

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'_\gamma}{E_\gamma} \right)^2 \left(\frac{E_\gamma}{E'_\gamma} + \frac{E'_\gamma}{E_\gamma} - \sin^2\theta \right)$$

- We can show that $$\frac{E'_\gamma}{E_\gamma} = \frac{1}{1+\varepsilon(1-\cos\theta)}, \text{ où } \quad \varepsilon = \frac{E_\gamma}{m_e c^2}$$
    - So $$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \frac{1}{[1+\varepsilon(1-\cos\theta)]^2} \left[1 + \cos^2\theta + \frac{\varepsilon^2 (1-\cos\theta)^2}{1+\varepsilon(1-\cos\theta)} \right]$$
    - At low energy (ε →0) $d\sigma/d\Omega \propto 1+\cos^2\theta$ the angular distribution is symmetric
    - At high energy (ε→∞) $d\sigma/d\Omega \propto \frac{1}{\varepsilon(1-\cos\theta)}$ the distribution peaks at *θ=0*
    - The energy of the scattered electron is maximal when *θ=π/2*

$$E_e^{\max} = \frac{E_\gamma}{1+1/(2\varepsilon)}$$

Compton Scattering



- Integrating over θ we get

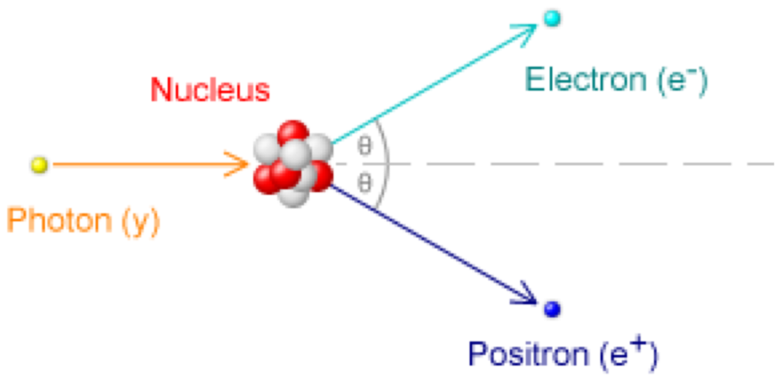
$$\sigma_c^e(\varepsilon) = 2\pi r_e^2 \left\{ \frac{1+\varepsilon}{\varepsilon^2} \left[\frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{1}{\varepsilon}\ln(1+2\varepsilon) \right] + \frac{1}{\varepsilon}\ln(1+2\varepsilon) - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right\}$$

  - At high energy $\sigma_c^e(\varepsilon) \propto \ln\varepsilon/\varepsilon$ thus the Compton scattering cross section decreases when the energy of the photon increases
- For an atom with *Z* atomic electrons
  - The cross section per atom is thus

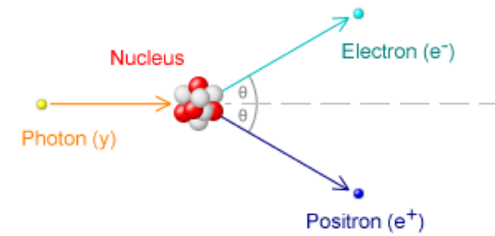
$$\sigma_c^{atome} = Z\sigma_c^e$$

Pair production

- Also known as photon conversion
- In the EM field of a nucleus, the photon can convert into an e^+e^- pair
  - Same Feynman diagram as Bremsstrahlung (to first order)
  - The interaction threshold is $E_\gamma \geq 2m_e c^2 + 2\frac{m_e}{M_N}c^2$
- This process cannot happen in vacuum (momentum conservation)
- But not much energy is carried by the nucleus (~1 MeV for large nuclei)



Pair production



- The cross section
  - At low energy

$$\sigma_{paire} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{2E_\gamma}{m_e c^2} - \frac{109}{54} \right) = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln 2\varepsilon - \frac{109}{54} \right) \quad \mathrm{cm}^2/\mathrm{atome}$$

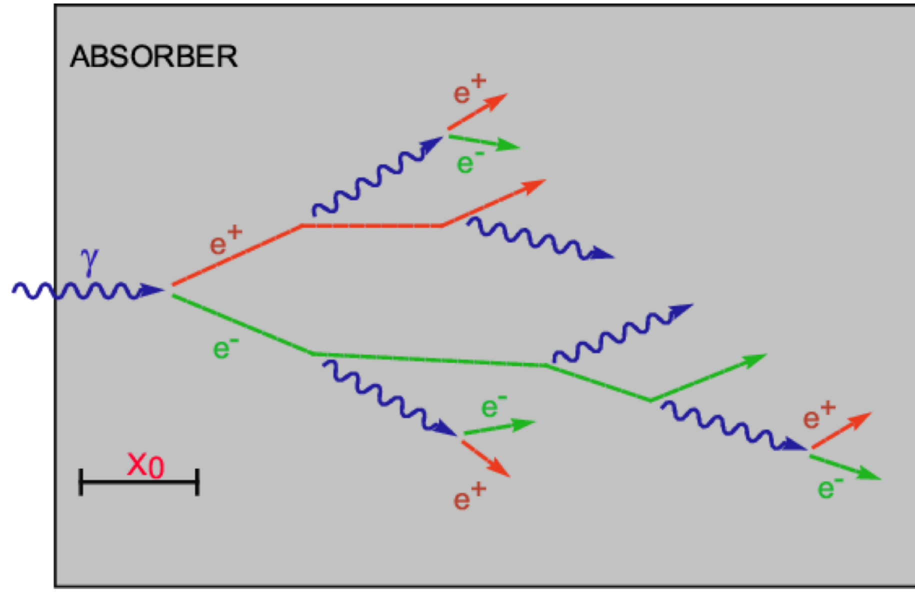
  - For energies above 1 GeV, a screening effect happens and becomes complete and thus

$$\sigma_{paire} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \approx \frac{7}{9} \cdot \frac{A}{N_A} \cdot \frac{1}{X_0} \quad \mathrm{cm}^2/\mathrm{atome}$$

  - The radiation length (en g/cm²) is $X_0 = A \Big/ \left(4\alpha N_a Z(Z+1) r_e^2 \ln \frac{138}{Z^{1/3}} \right)$
    - The cross section is independent of the photon energy for E_γ > ~ 1 GeV, only depends on the medium (X_0)
- The photon conversion probability per unit length is $w = N_A \left(\sigma_{paire} / A \right) \cdot \rho = \frac{7}{9} \cdot \frac{\rho}{X_0}$
  - The mean free path for a photon before it converts $\lambda_{paire} = 1/w$
  - If we put X_0 back into units of cm, we have $w = \frac{7}{9} \cdot \frac{1}{X_0}$, donc $\lambda_{paire} = \frac{9}{7} X_0 \approx X_0$

EM showers

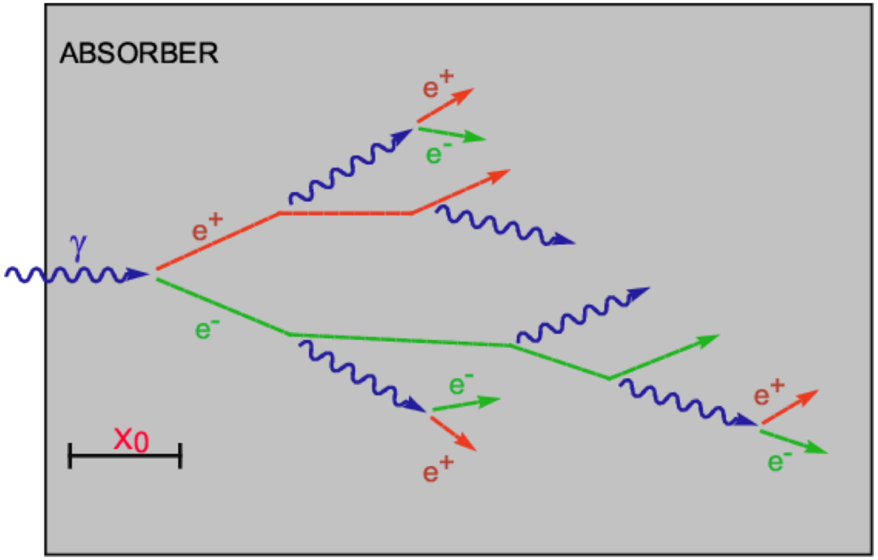
- At high energy ($E_\gamma \gtrsim 1$ GeV),
  - Electrons loose their energy almost exclusively through Bremsstralung
  - Photons loose their energy by pair production
  - The combination of these two effects leads to the creation of EM showers when an electron or photon enters a heavy medium



- The shower development is a statistical process
  - The rigorous calculation is done by Monte Carlo simulation
  - Nonetheless, a simple model describes well, on average, this process
    - An electron with $E>E_C$ looses energy $E/2$ by Bremsstrahlung after having traversed a thickness X_0
    - A photon with $E>E_C$ produces an e^+e^- pair after having traversed a distance X_0
    - Electrons with $E<E_C$ loose all their energy by ionisation (the Bremsstrahlung loss is neglected)
    - Ionisation energy loss is neglected for electrons with $E>E_C$

EM showers

- Starting from a photon with energy E_0 : after a distance
  - $1X_0$: production of 2 particles: e^+ et e^- each with an energy $E_0/2$
  - $2X_0$: Bremsstrahlung: 4 particles: $\gamma e^+ \gamma e^-$ each with an energy $E_0/4$
  - … etc. After each radiation length, have twice as many particles, each with half the energy. After tX_0
    - $E(t) = E_0/N(t) = E_0 / 2^t$
  - The shower development stops when $E(t) = E_c$
    - $t_{max} = \ln(E_0/E_C)/\ln(2)$



STRONG INTERACTION OF HADRONS

Strong interaction of hadrons

- The strong interaction between hadrons and nuclei is very short-ranged (~10^{-15}m)
  - Interactions very rare relative to EM processes
  - But for high energy hadrons (E > 1 GeV) and when the medium is dense: strong interactions dominate
- Consider the total cross section as: $\sigma_{total} = \sigma_{elastic} + \sigma_{inelastic}$
- In elastic processes (dominant at low energy)
  - The hadron remains intact after the interaction

Strong interaction of hadrons

- In inelastic interactions
  - Secondary hadrons are produced
    - e.g. p+N → p,n,π, K,..
  - We cannot identify the incoming hadron after the interaction
    - We say it has been 'absorbed'
  - The absorption probability per unit length

$$w_a = N_A(\sigma_a / A) \cdot \rho = N_A(\sigma_{inélastique} / A) \cdot \rho \text{ cm}$$

  - The nuclear absorbtion lenth (mean free path)

$$\lambda_a = 1/w_a = A/(N_A \rho \sigma_{inélastique}) \text{cm} \quad \text{ou} \quad \lambda_a \rho = 1/w_a = A/(N_A \sigma_{inélastique}) \text{g} \cdot \text{cm}^{-2}$$

  - The nuclear interaction length

$$\lambda_{nucl} = A/(N_A \rho \sigma_{totale}) \text{ cm} \quad \text{ou} \quad \lambda_{nucl} \rho = A/(N_A \sigma_{totale}) \text{ g} \cdot \text{cm}^{-2}$$

- Cross sections depend on energy and type of hadrons
  - At low energy, the energy dependence is complicated because of resonances
  - At high energy
    - σ_{totale} depends on $ln(E_{cm}^2) = ln(s)$
    - The mean number of secondary hadrons produced in an interaction depends on E in the same way
      - ~90% or secondary hadrons are pions (π)

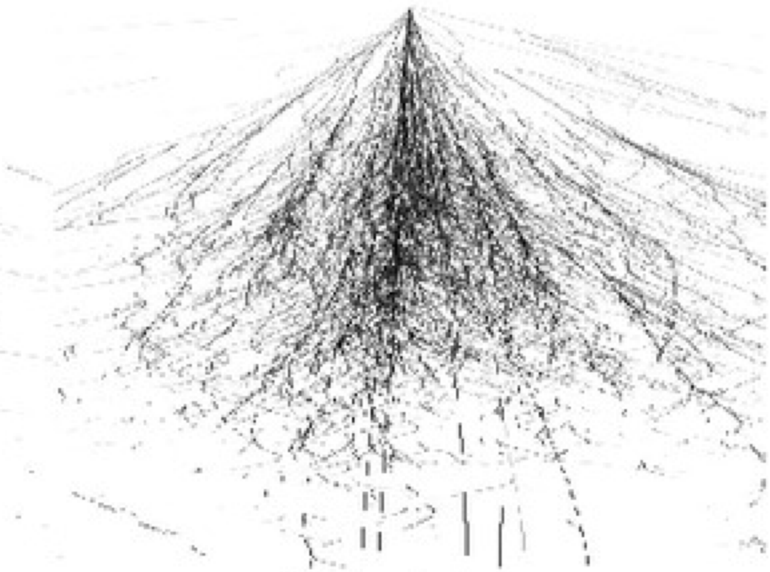
Hadronic showers

- A hadronic shower is initiated by the secondary hadrons produced in the inelastic interactions of a high energy incident hadron
  - On average, half of the energy of the incident hadron is transferred to the secondary hadrons, the rest is shared between slow pions and other processes
- The longitudinal development of a hadronic shower is characterised by the nuclear absorption length (λ_{nucl})
  - As $\lambda_{nucl} >> X_0$ hadronic showers form deeper into the material than EM showers
  - Secondary hadrons have larger transverse momentum (transverse to the direction of the incident hadron) than found in EM showers
  - The size of hadronic showers will thus be larger
- The fluctuations during the development of hadronic showers is large
  - The energy measurement of a hadron is less precise than that of an electron/photon

Strong interaction of hadrons

- Neutrons
  - The neutron penetrates far as it only sees the strong force
  - High energy neutrons (E >~100 MeV) interact in the medium like charged hadrons, result in a hadronic shower

Gamma shower



Hadronic shower

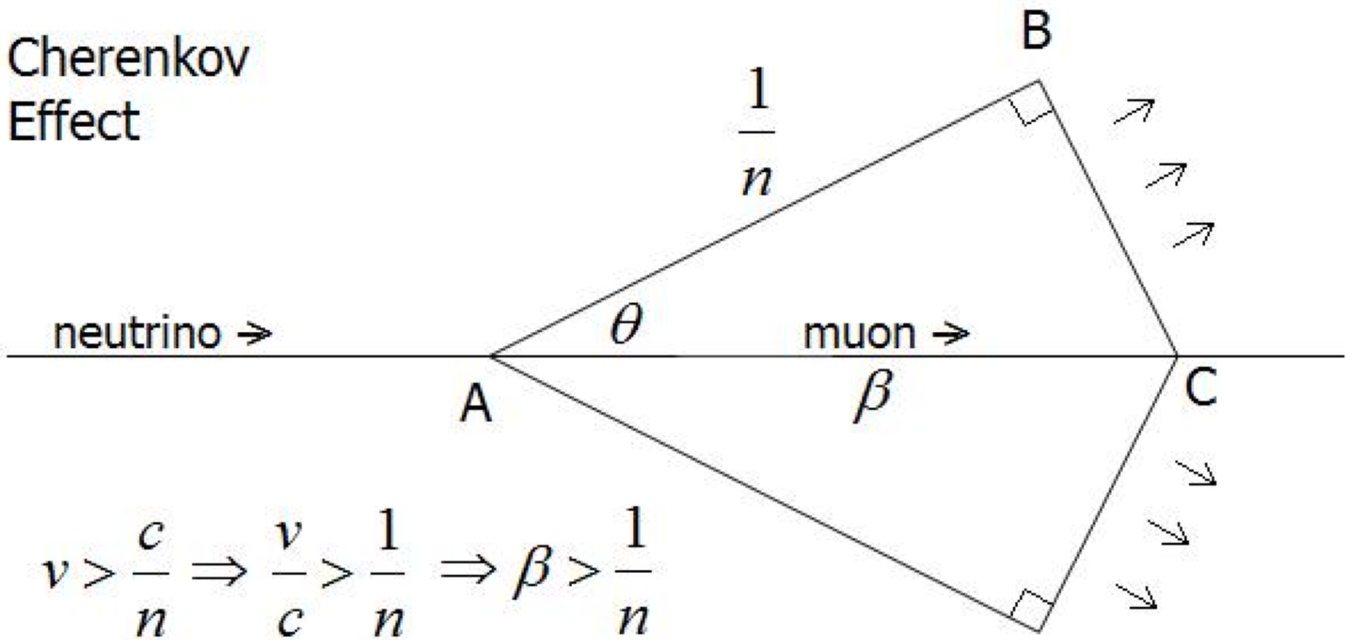
CHERENKOV RADIATION

Cherenkov Radiation

- A charged particle of velocity *v* traverses a medium of refraction index *n* and polarises the atoms along its path
  - These atoms become electric dipoles
  - These dipoles emit EM radiation
- If the speed of the particle doesn't exceed the speed of light in the medium ($v<c/n$)
  - The dipole radiation from the two sides of the path cancel
- If instead $v > c/n$
  - The downstream material cannot be polarised
  - The field created by the particle propagates less fast than the particle itself
  - Resulting in a net radiation emission
  - This is the Cherenkov effect
  - Analogy: a plane breaking Mach 1

Cherenkov Radiation

- The angle of the net radiation emitted is determined by the speed of the particle (and the refactive index of the medium)
- Simple geometric calculation



$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

Cherenkov Radiation

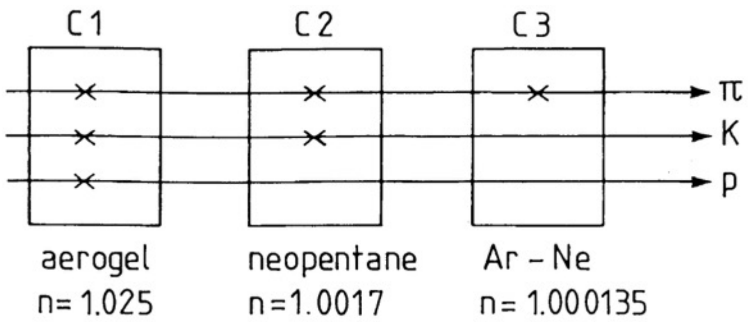
- The exact calculation takes into account the recoil of the charged particle
  - Can be computed using classical electrodynamics

$$\cos\theta_c = \frac{1}{n\beta} + \frac{\hbar k}{2p}\left(1 - \frac{1}{n^2}\right),$$

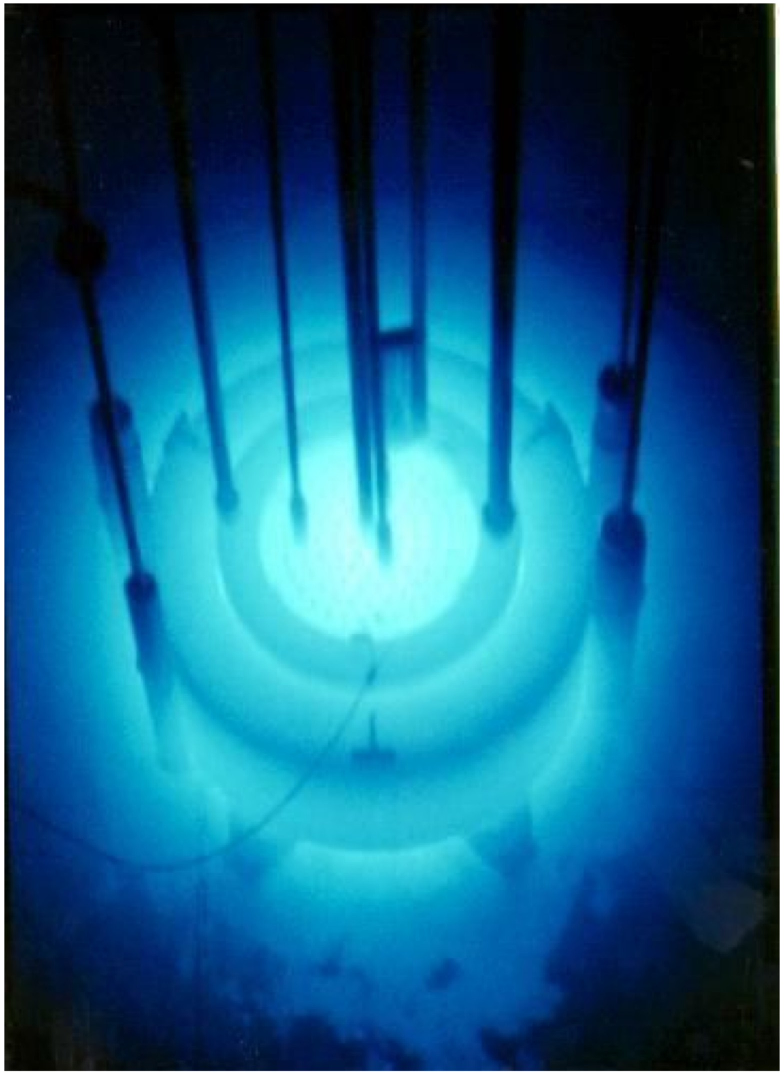
  - Where $\hbar k$ is the momentum of the photon, and p is the momentum of the charged particle
- Cherenkov radiation happens in all transparent mediums
- Energy loss due to Cherenkov radiation is negligeable
  - Scintillation is 100 times more intense
- Radiation threshold is $\beta > 1/n$
  - At the threshold, the radiation is emitted in the direction of the particule ($\theta_c = 0$)
- Can exploit these different thresholds to distinguish particles with the same momentum (*p*) but different masses
  - The mass threshold is given bs

$$m_{th} = \frac{p\sqrt{1-\beta_{th}^2}}{\beta_{th}} = p\sqrt{n^2 - 1}$$

  - Particles heavier than m_{th} will not emit light

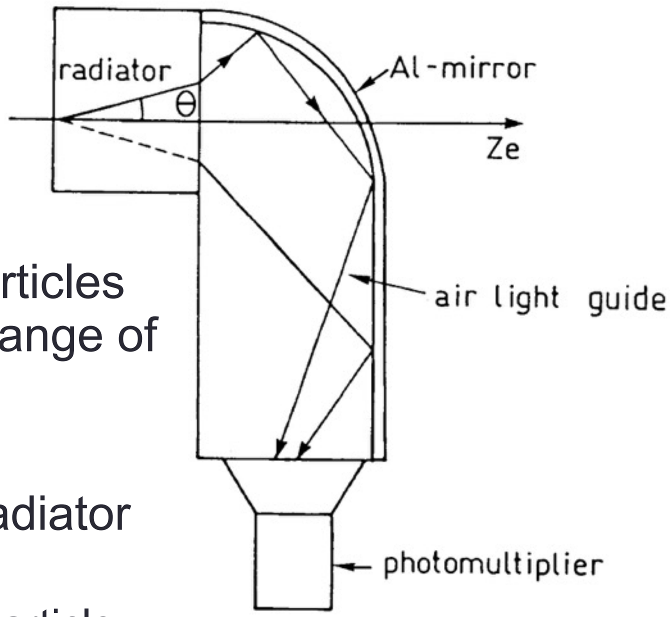


Cherenkov Radiation



Cherenkov radiation due to fission

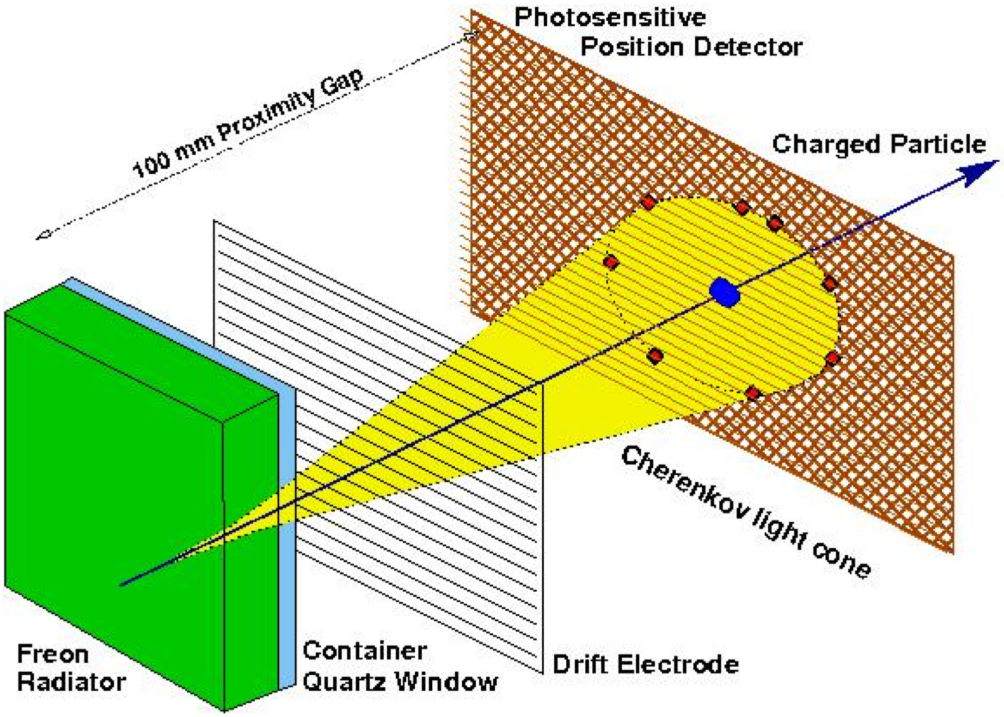
Cherenkov Detectors

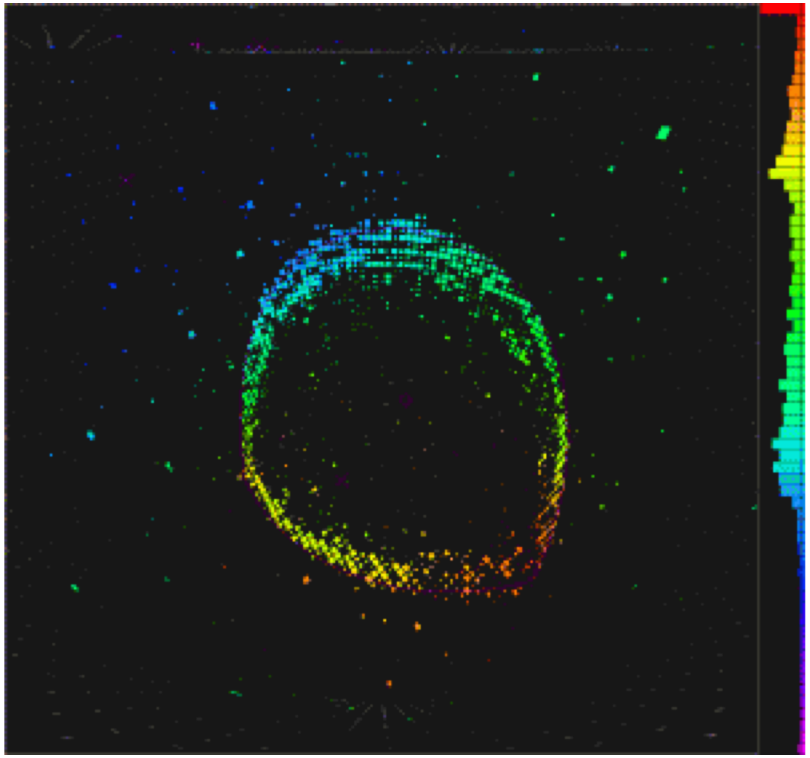


- Differential counters
  - Can use Cherenkov light to only be sensitive to particles in a particular range of energy (or more precisely range of speeds)
  - β_{min} is determined by the threshold 1/n
  - β_{max} is given by the internal reflection between a radiator and a light guide
    - The reflection angle increases with the speed of the particle
    - If the speed is above a certain threshold, the reflection angle is larger than the critical reflection angle needed to propagate along the wave guide
  - Examples
    - Often use diamond (n=2.42) as radiator
      - β_{min} ~0.413 and β_{max} ~0.454
      - Gives a selection window of $\Delta\beta$ ~0.04 i.e. $\Delta\beta/\beta$ ~10%
    - The best differential counters can get a resolution as good as $\Delta\beta/\beta \sim 10^{-7}$

Cherenkov Detectors

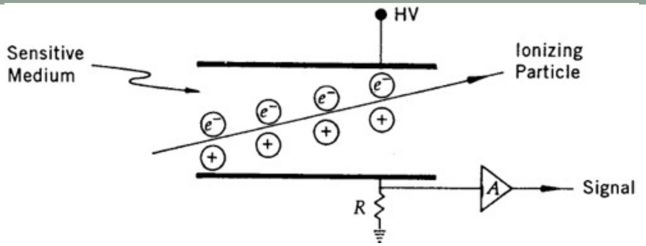
- Annular imaging
  - RICH (ring imagine Cherenkov)
  - The goal is to detect the cone of light emitted by a particle, to identify the type of particle and its speed





Muon in superKamiokande

IONISATION DETECTORS

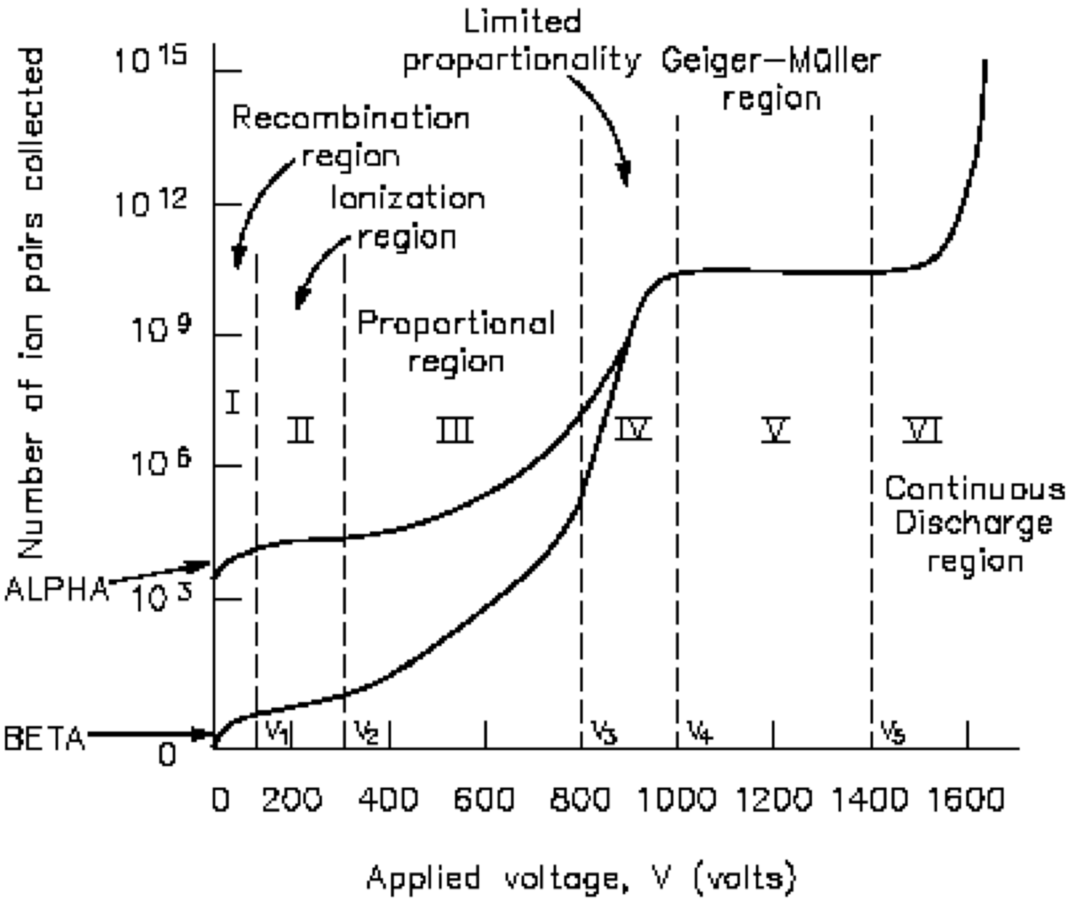


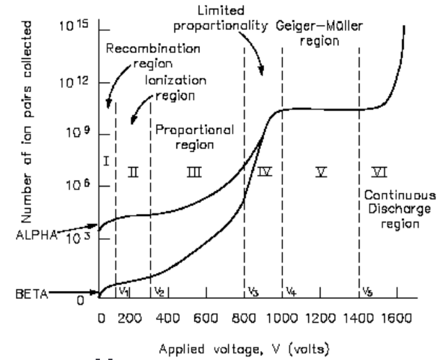
Ionisation detectors

- These detectors pick up the presence of a charged particle by measuring the total charge of electrons or ions produced by the ionisation of the medium traversed
  - This medium could be a gas, a liquid or a solid
- In order to pick up the electrons or ions before they recombine into neutral atoms, need an electric field that causes them to drift towards electrodes
- The drift charges induce a current on the electrodes
- These currents are detected by amplifiers that produce a measurable electrical signal
- The mean number of electron-ion pairs produced is given by the Bethe-Block formula
  - $N_I = -dE/dx \, d/W$
    - Where *d* is the thickness of the detector, W is the mean energy needed to create an electron-ion pair
    - In a gas: W ~ 30 eV
- The total charge picked up by the amplifier depends on many technical factors, in particular the strength of the applied electric field

Ionisation detectors

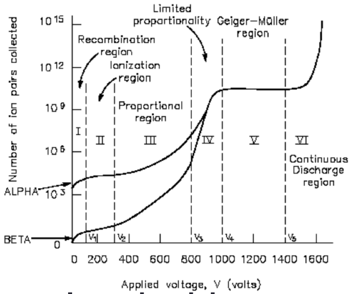
- Operational regions of an ionisation detector
  - Depend on the voltage (i.e. the electric field applied)





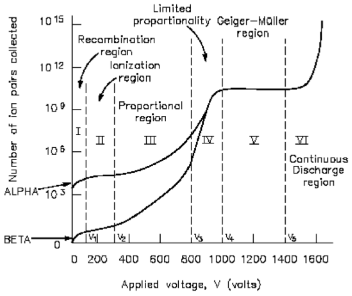
Ionisation detectors

- Recombination region
  - When the electric field between the electrodes is weak
  - Electrons-ion pairs can re-combine into neutral atoms as soon as they are produced
  - Only a small fraction of the ionisation charge is picked up by the amplifiers
  - Use: mostly for calibrating other radiation detectors
    - e.g. http://rpd.oxfordjournals.org/content/9/2/123.short
- Ionisation region
  - When the voltage is high enough to stop re-combinations, most of the ionisation charges produced drift towards the electrodes
  - The signal obtained reflects the total ionisation charge
  - Disadvantage: signal is still quite weak as no amplification of the charge inside the active medium
    - Need to use special low noise amplifiers
  - Advantage: excellent energy resolution and very good linearity
  - Use: ionisation chambers
    - e.g. liquid Ar chambers, Silicon/Germanium detectors



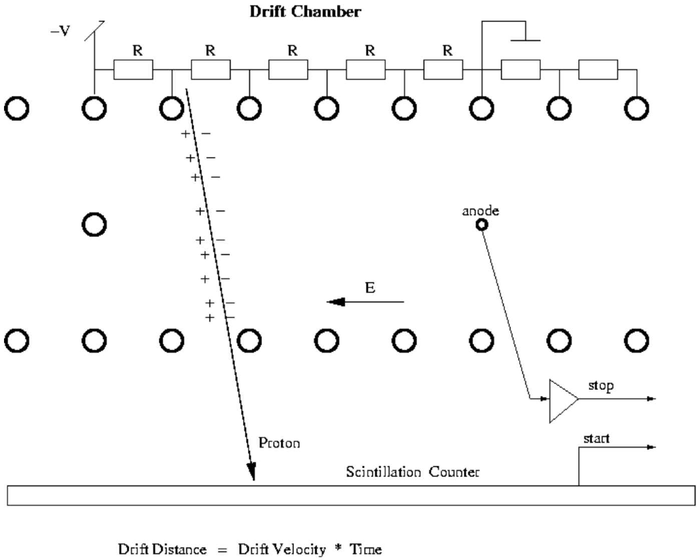
Ionisation detectors

- Proportional region
  - If the applied field is sufficiently high ($E \sim 10^4$ V/cm) the electrons will be accelerated by the electric field and gain enough energy to produce secondary ionisations
  - The secondary ionisation probability per unit length (α) is constant for a given electric field
  - The total number of ionised atoms is thus proportional to the initial number of ionisations
    - $N_{total} = N_0 e^{\alpha d}$
  - The amplification factor (often called gain): $M = e^{\alpha d} \sim 10^4 – 10^8$
  - With a gas, we can get a big amplification factor
    - Most detectors operating in this region are thus gas detectors
  - Advantage: no need for low noise electronics
  - Disadvantage: energy precision isn't as good because of fluctuations of the amplification process (sensitivity to the value of M)
    - These fluctuations are due to variations of 'control parameters': HV, temperature,..
  - Often use these detectors to measure the position of particles
    - Drift chambers
    - Proportional wire chambers
  - As the particles loose very little energy in the gas, a wire drift chamber is ideal for measuring the tracks of charged particles in front of a calorimeter whose goal is to measure their energy (minimal interference)



Ionisation detectors

- Examples of proportional region detector configurations



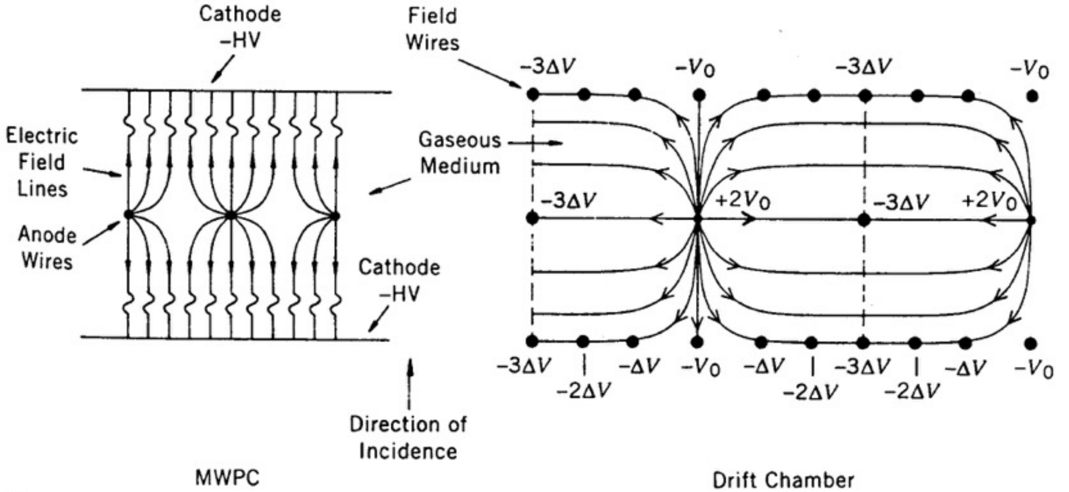
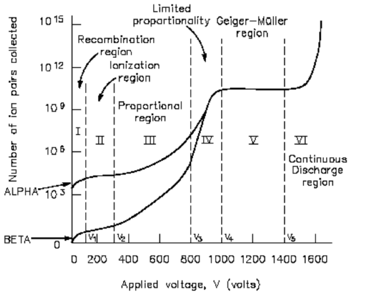
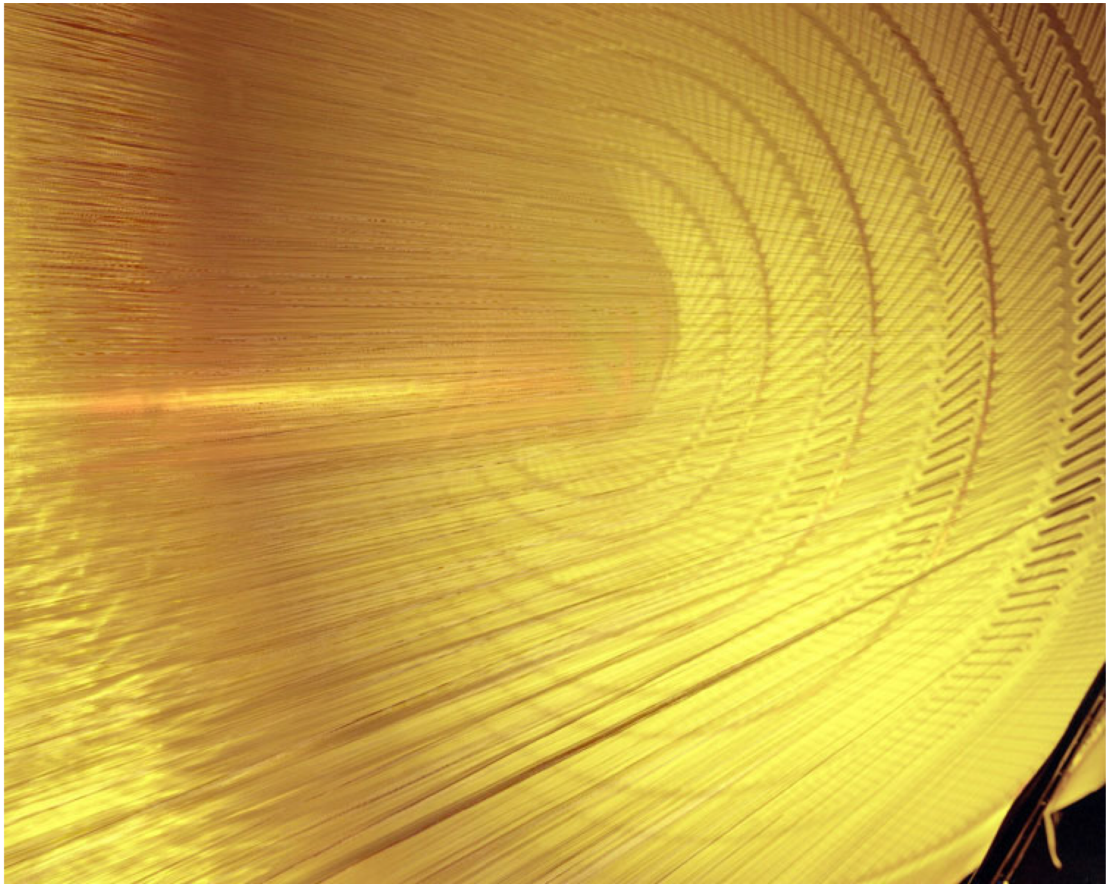


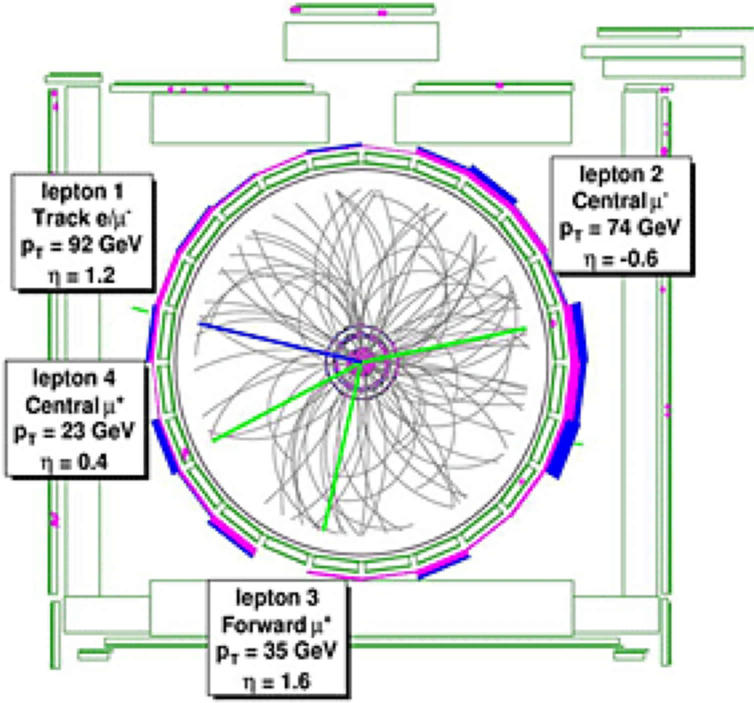
Figure 7.3 Electric field structure in a multiwire proportional chamber and in a multiwire drift chamber.

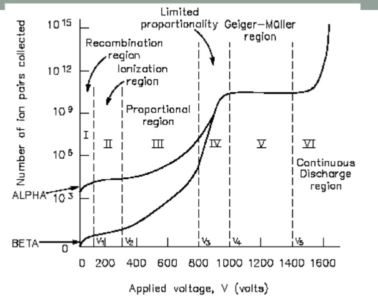


Ionisation detectors

- Examples of proportional region detector configurations





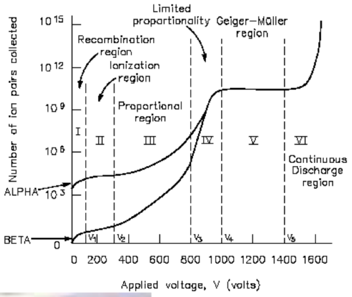


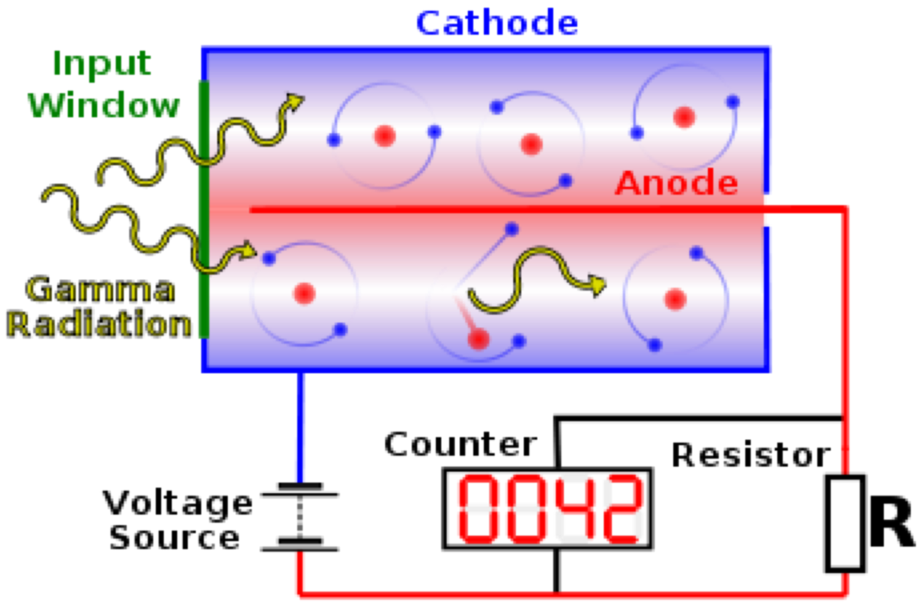
Ionisation detectors

- Geiger region
  - If we increase the field even further, the energy of the electrons from the primary ionisations increase rapidly and they excite or ionise immediately other atoms
  - An electron avalanche is produced
  - A large number of photons are produced during the atomic de-excitation process
  - These photons trigger themselves ionisation avalanches through the photo-electric effect, along the anode wire where the electric field is strongest
  - These avalanches happen very quickly and an audible discharge is heard
  - That's the principle of the Geiger counter
  - The discharge only stops when the total charge due to the positive ions around the anode decreases the electric field enough that the multiplication process cannot continue
  - The detector will not be sensitive to new ionisation until the ions have drifted far enough away from the anode
    - That's the reason for the dead-time in Geiger counters
  - During a discharge, the current on the anode is saturated
    - The amplification of the signal is independent of the primary charge
  - Disadvantage: cannot measure the energy
  - Advantage: can measure radiation rate, even for very low radiation levels

Ionisation detectors

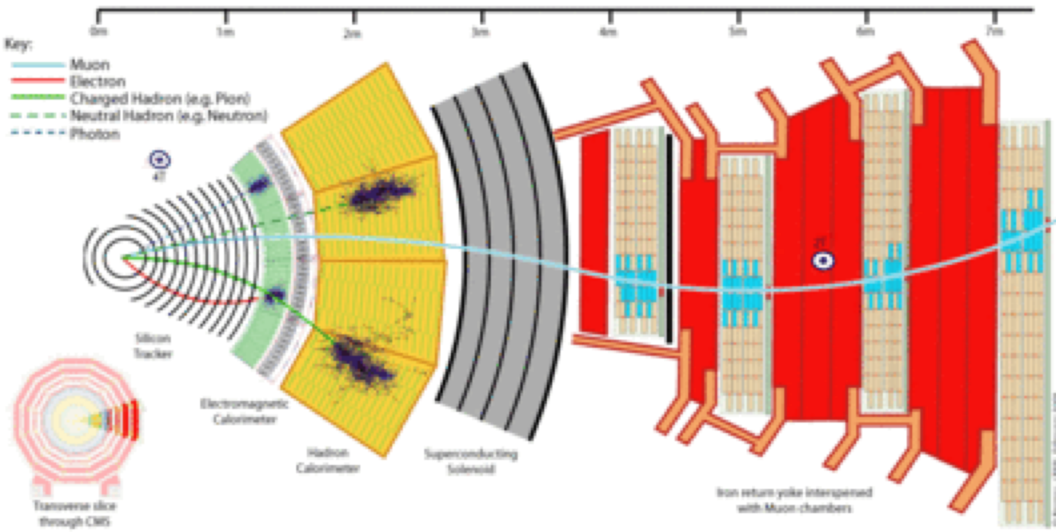
- Geiger region: examples

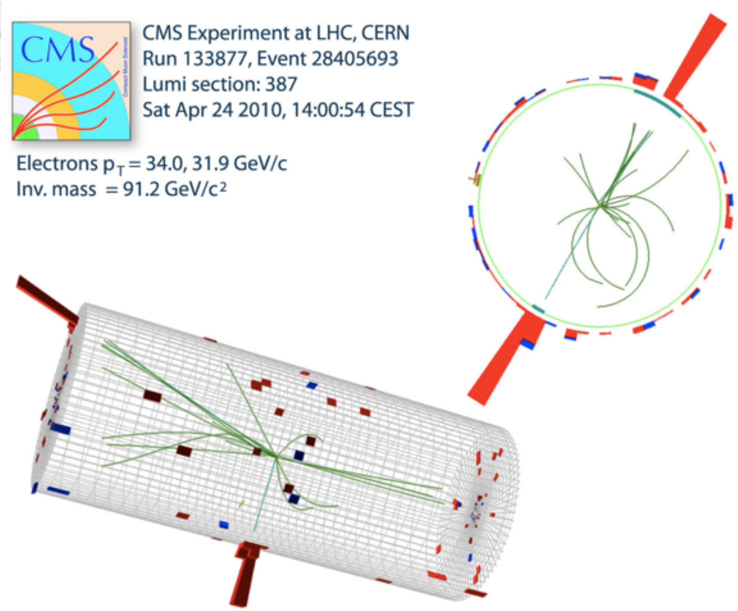




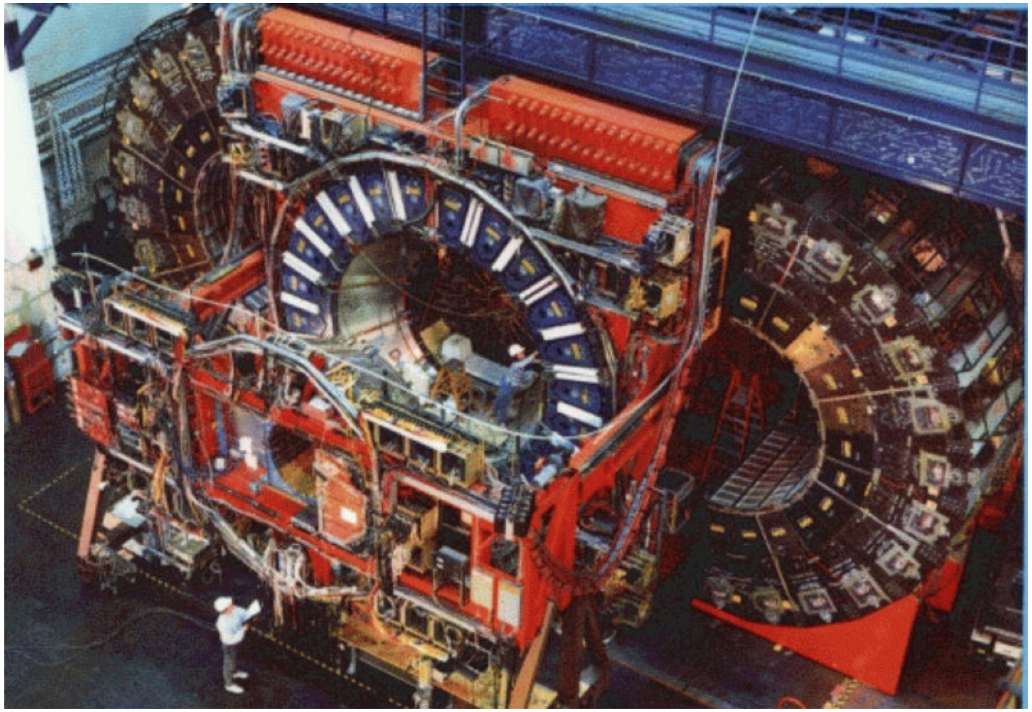
BACKUP SLIDES

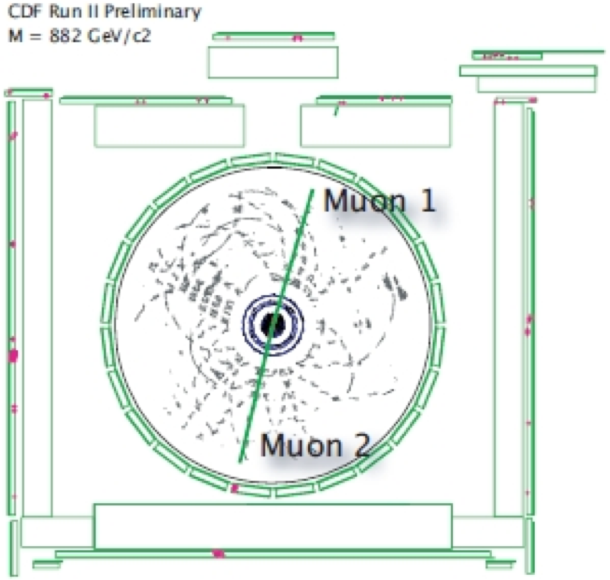
Full Detectors: CMS

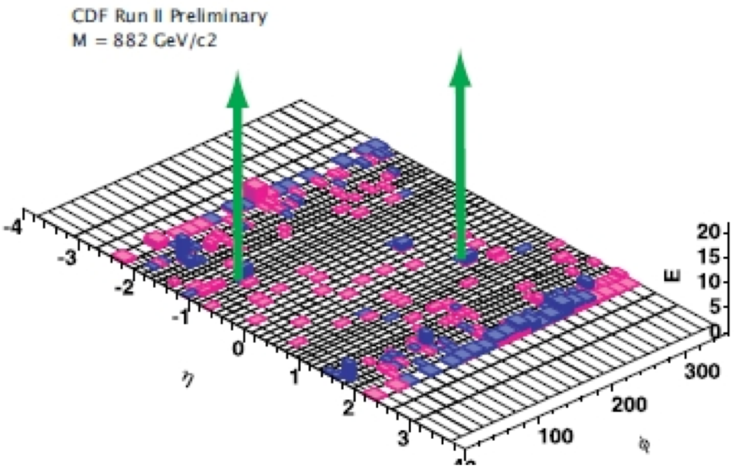




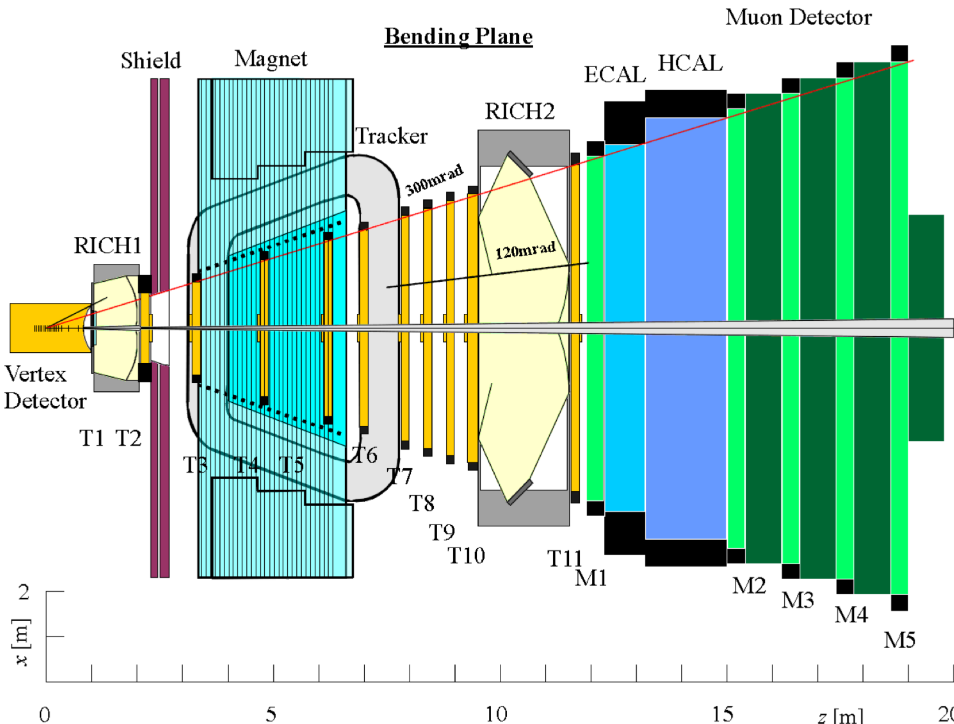
Full Detectors: CDF

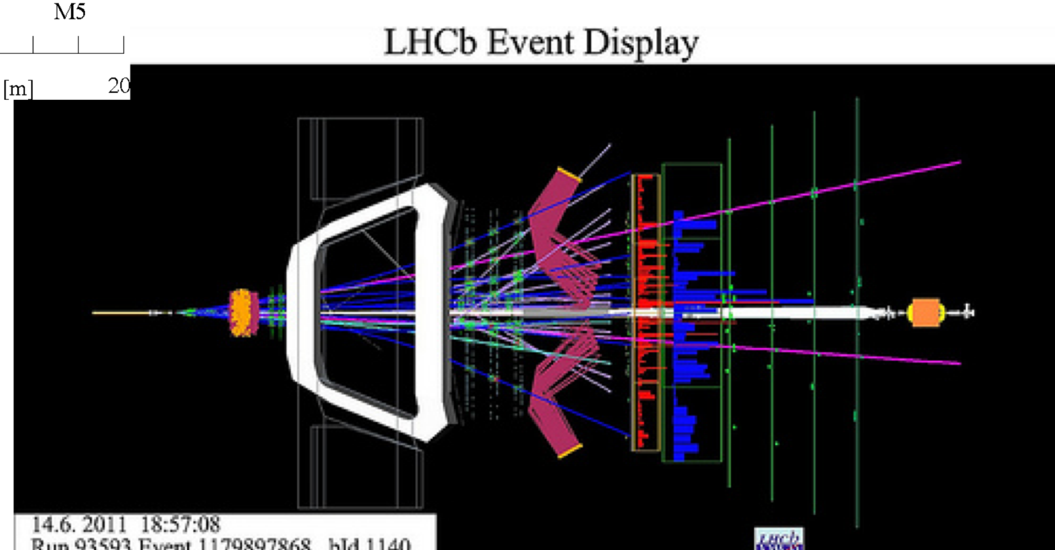




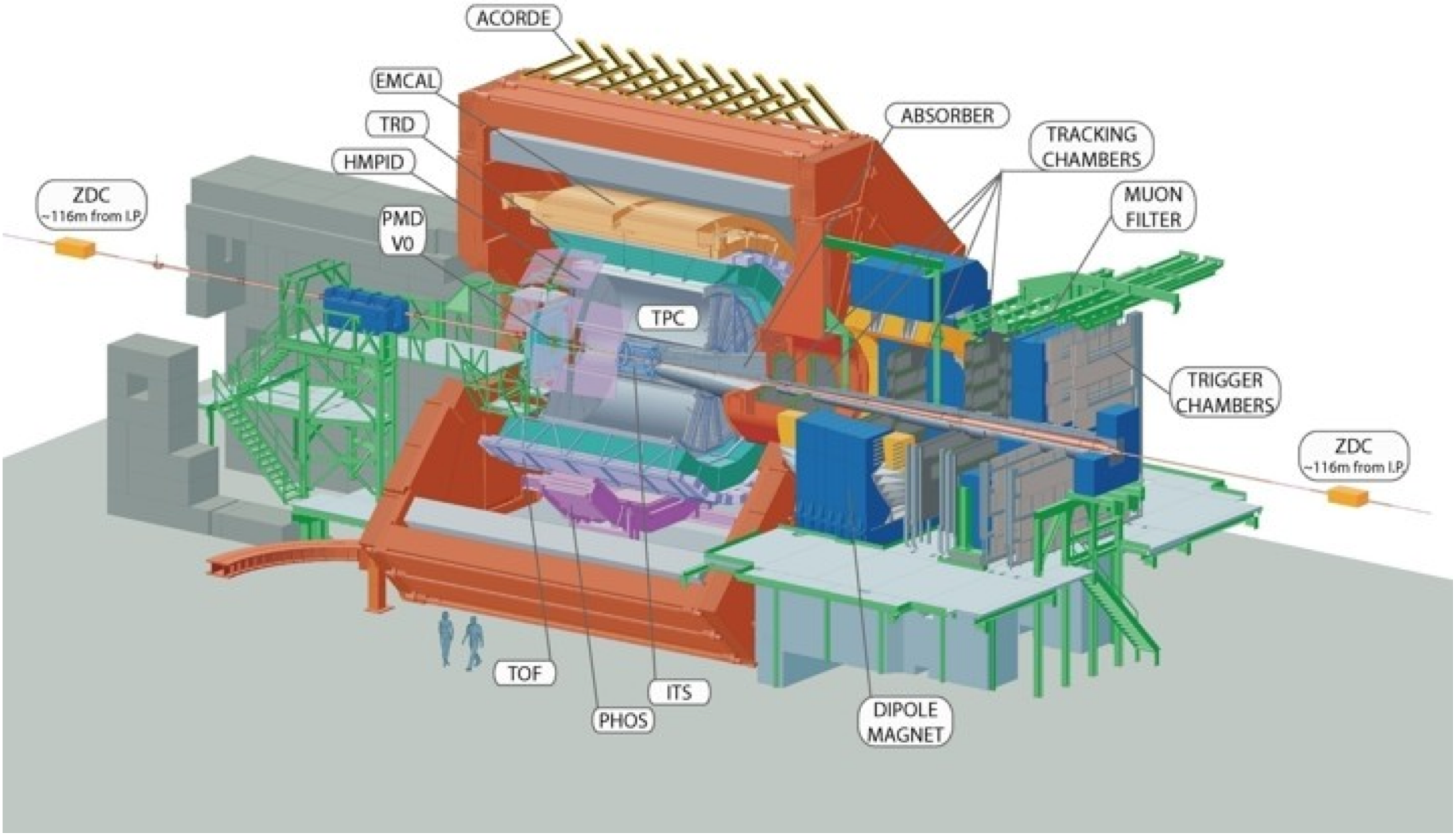


Full Detectors: LHCb



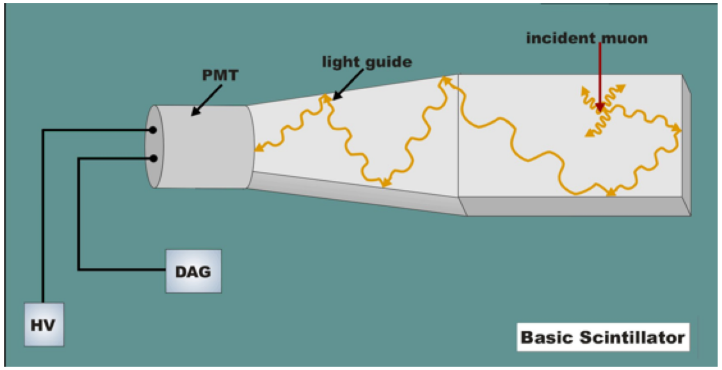


Full Detectors: ALICE



Scintillation detectors

- Dans certains matériaux transparents
  - Une particule chargée excite un atome
  - L'atome se désexcite en émettent une petite quantité de lumière
  - Le matière émet une petite quantité de lumière (fluorescence)
    - Oui comme les ampoules (http://fr.wikipedia.org/wiki/Tube_fluorescent#Techniques)
  - Ces photons peuvent être détectés par un détecteur photosensible si le milieu est transparent pour au moins partie des longueur d'ondes émissent
  - Exemples de matériaux qui remplissent ces conditions de transparence
    - Scintillateurs organiques (plastique, liquide, cristal)
      - Etats excités des molécules sont la source de fluorescence
    - Scintillateurs inorganiques (cristaux): NaI(Ti), PbWO4, BGO,…
      - C'est les états intermédiaires d'impuretés qui sont la source de lumière fluorescente



Scintillation detectors

- Caractéristiques de scintillateurs
  - Le temps de montée ('rising time') et la constante de temps
    - Les scintillateurs sont très rapides
      - Le temps de montée est de ~1 ns
      - Plus rapides que les détecteurs d'ionisation
    - Le nombre de photons après le maximum suit une loi exponentielle avec une constante beaucoup plus grande ~100 ns
  - L'efficacité: l'énergie nécessaire pour créer un photon
    - NaI(Ti): 20 eV
    - Plastique: 100 eV
    - BGO: 200 eV
  - Linéarité de la réponse
    - dN/dE indépendante de E
    - Sauf à très basse énergie
- Permet d'utiliser les scintillateurs
  - Dans les calorimètres
  - Dans le 'trigger'

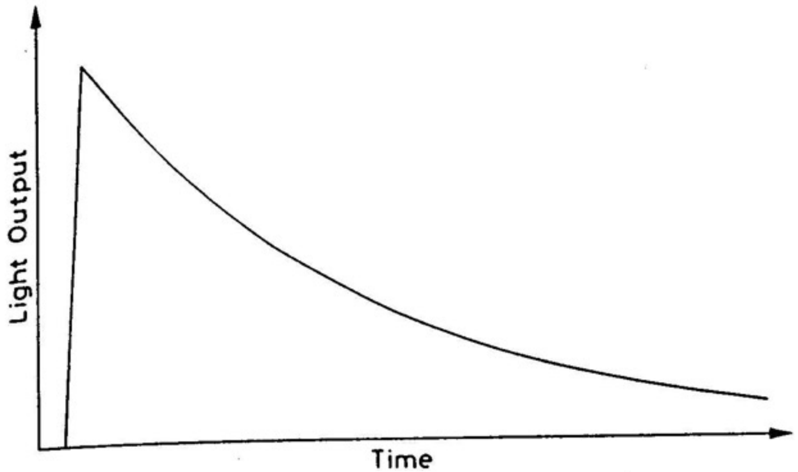


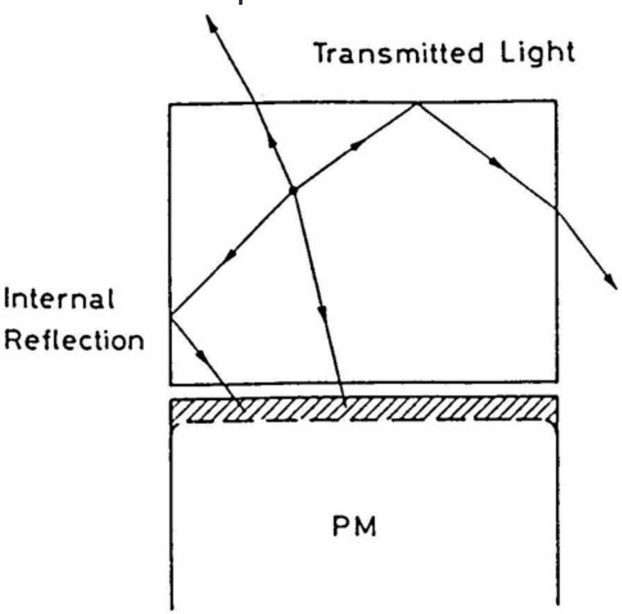
Fig. 1 Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

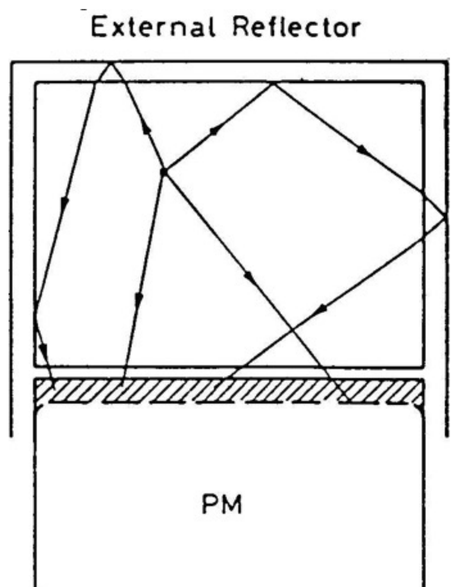
Scintillation detectors

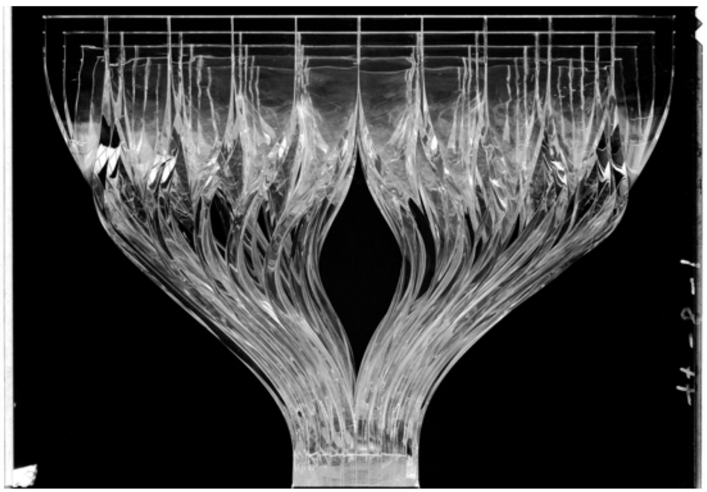
- Caractéristiques de scintillateurs (suite)
  - Le spectre des photons est étroit
    - Plastique: 423mn
    - NaI(Ti): 413nm
    - BGO: 480nm
    - Le photo-détecteur (souvent photomultiplicateur) doit être adapté au matériau utilisé
    - Parfois un dopant est ajouté pour décaler la longueur d'onde pour qu'elle soit mieux adaptée au photomultiplicateur
      - Le dopant absorbe les photons de scintillation et réémet rapidement (~1ns) des photons avec une autre longueur d'onde
  - La longueur d'atténuation
    - Les photons doivent traverser le scintillateur pour arriver aux éléments photosensibles
    - Certains photons seront réabsorbés en route
    - Le nombre de photons non-absorbés en fonction de la distance parcourue suit une loi exponentielle $N(x) = N_0 e^{-x/\lambda}$ ou λ est la longueur d'atténuation
    - En général λ ~1m
    - On peut donc construire de grands détecteurs

Scintillation detectors

- Collection des photons
  - But est de réduire au minimum la perte des photons dans le milieu
    - Pertes par absorption
    - Pertes par fuite
  - On utilise
    - Réflexions internes
      - Réflexion totale: $\sin\theta_c = n_{air} / n_{scint}$ alors $\theta_c \sim 39$ degrés pour un plastique
    - Réflexion par miroir: paroi le plus lisse possible
  - On utilise de la colle est du gel pour joindre les éléments et réduire la réflexion
  - Des guides de lumière sont utilisés pour adapter la géométrie ou transporter la lumière
    - On peut aussi les utiliser pour faire un shift du spectre ('wave length shifters')

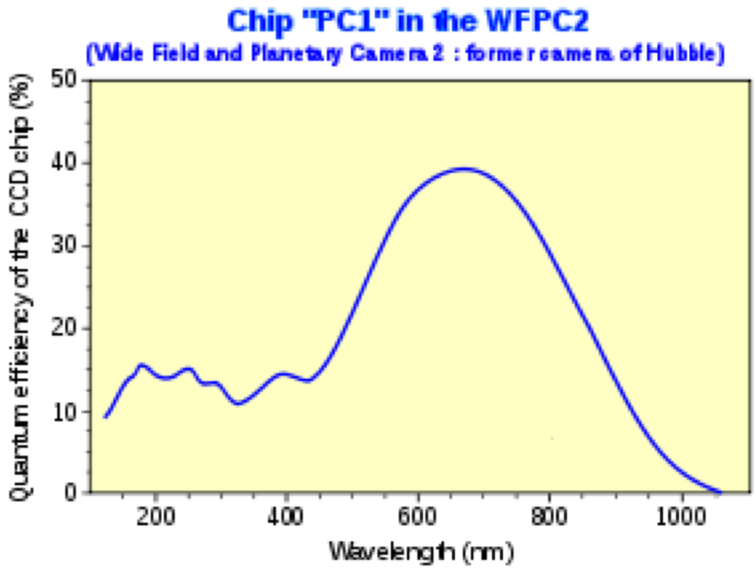






Scintillation detectors

- Les photomultiplicateurs
  - But: convertir les photons de scintillation en un signal électrique
    - Qui peut être traité électroniquement (amplification,..)
  - Le principe physique est l'effet photo-électrique
    - Produit pas un photocathode
      - En général une fine couche d'un alliage métallique alcalin
      - L'efficacité quantique (η): le nombres de photoélectrons créés par photon incident
        - Typiquement: $\eta \sim 0.25$
        - Dépend de la longueur d'onde du photon



Plot du chip CCD du Hubble Space Telescope's Wide Field and Planetary Camera 2.

Scintillation detectors

- Les photomultiplicateurs (suite)
  - Derrière le photocathode se trouve un série (10-14) d'électrodes dites 'dynodes' formés d'un alliage particulier (souvent du CuBe) portés à des potentiels électriques croissants
  - Les photoélectrons émis par le photocathode sont accélérés et focalisés sur la première dynode
    - Ils arrachent 2-5 électrons par photoélectron
    - Amplification du signal
    - Et ainsi de suite par dynode
    - Gain total peut atteindre 10^7 après 14 dynodes
- L'efficacité d'un détecteur à scintillation dépend donc de plusieurs facteurs
  - Longueur d'atténuation
  - Perte des photons
  - Efficacité quantique

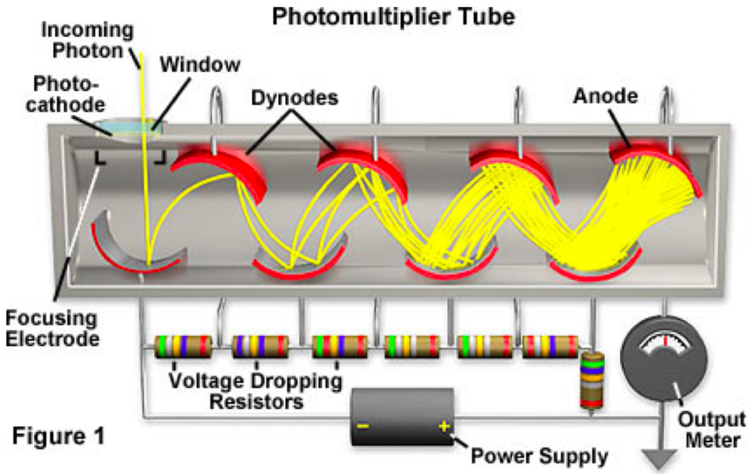
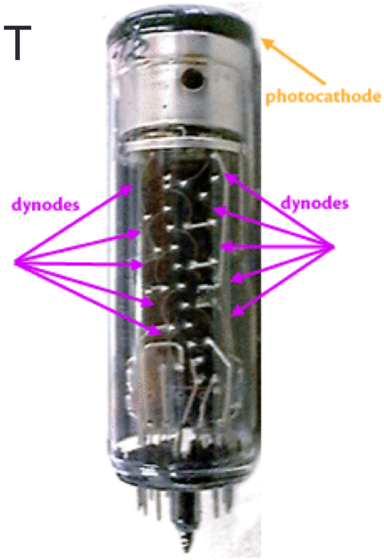
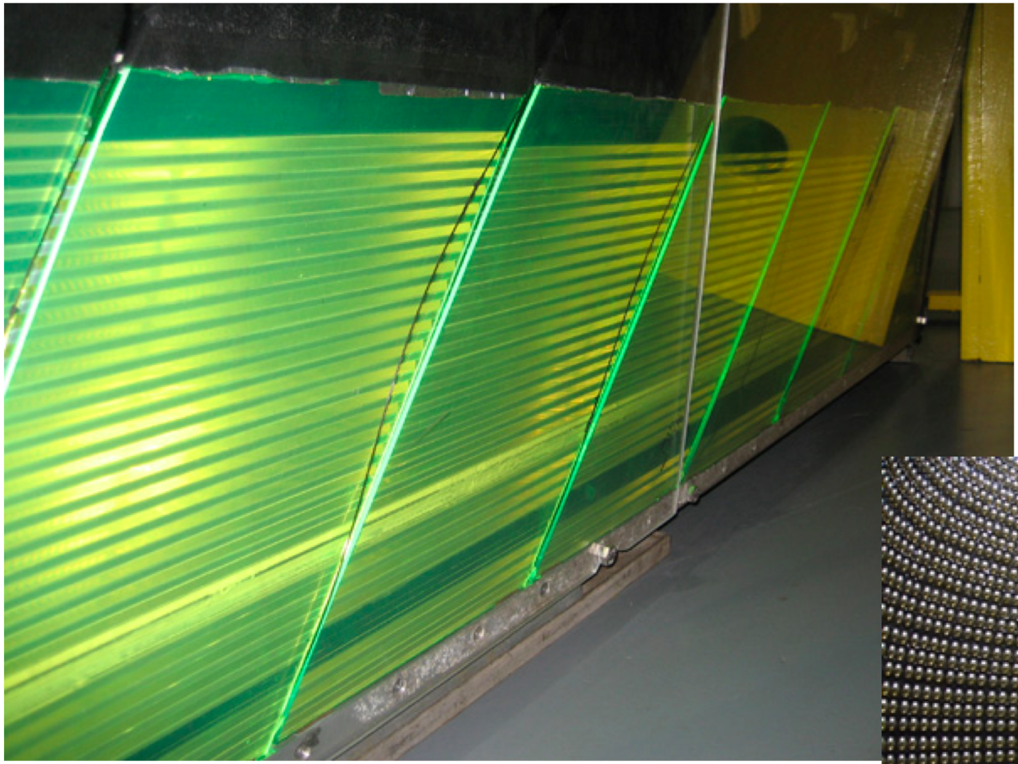


Figure 1

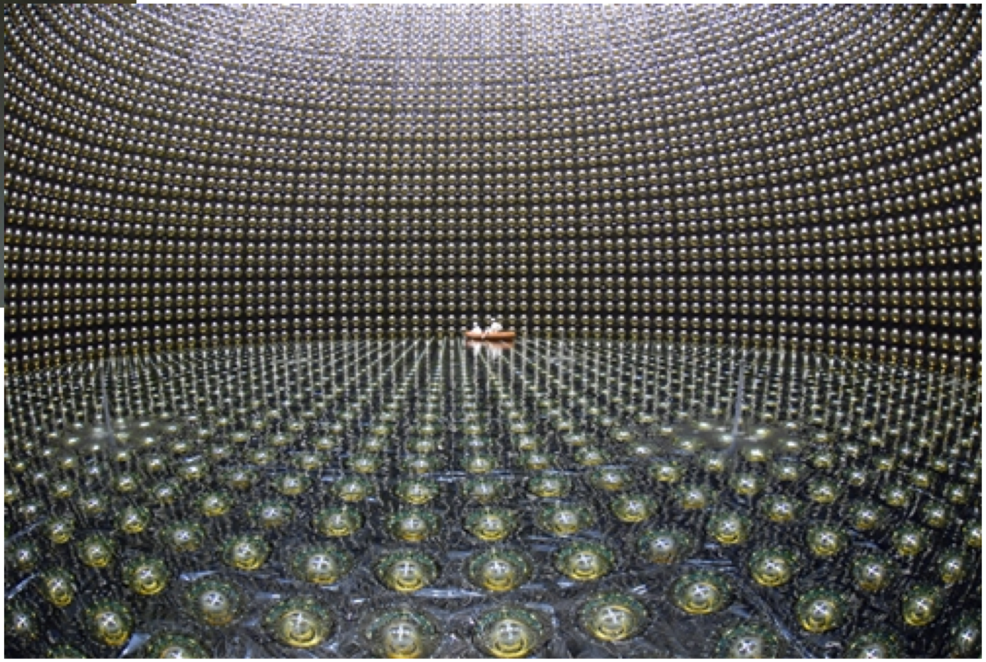
Scintillation detectors

PMT





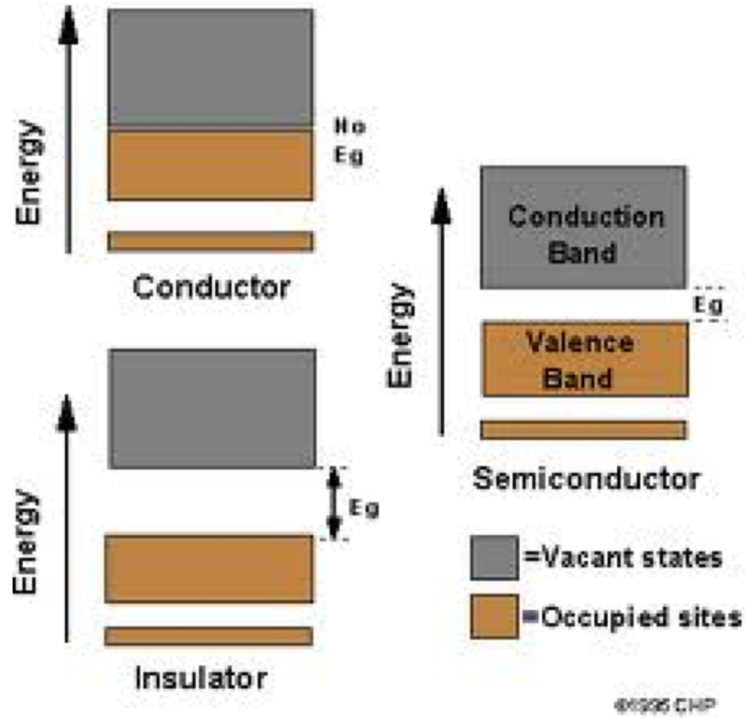
Calorimètre de CDF



Quelqu'un peut deviner?

Semiconductor detectors

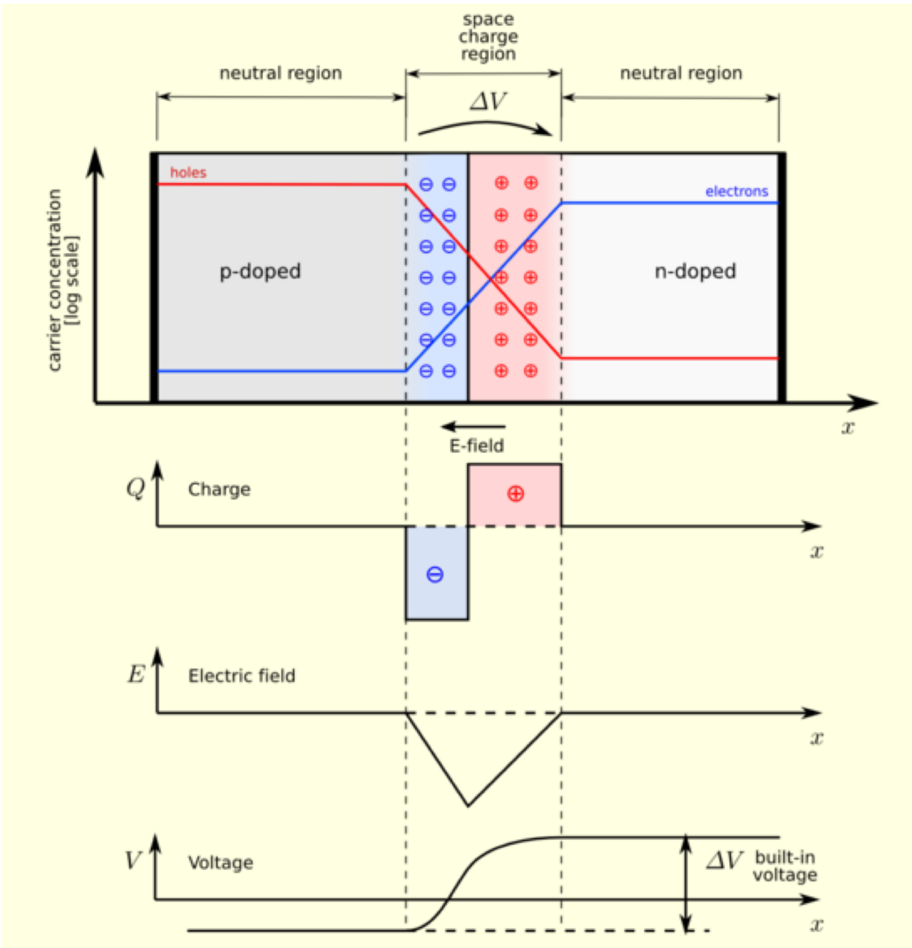
- C'est un type particulier de détecteurs à ionisation
- Une particule chargée traversant le milieu
  - Ne va pas exciter ou ioniser le milieu
  - Mais va créer des paires d'électrons-trous quasi-libres dans la bande passante
- Il faut seulement 3 eV pour créer une paire
  - Dans un gaz il faut 30 eV pour une ionisation
- Les charges crées peuvent être détectées en appliquant un champ électrique
- Avantages
  - Très bonne résolution en énergie
  - Compacte comme c'est un solide
  - Idéal pour un traceur
    - Précis (micro-bandes ou pixels)
    - Mince (petit X_0 et λ_0)
    - Rapide
- Désavantages
  - Cher
  - Fragile
  - Performance se dégrade avec l'irradiation

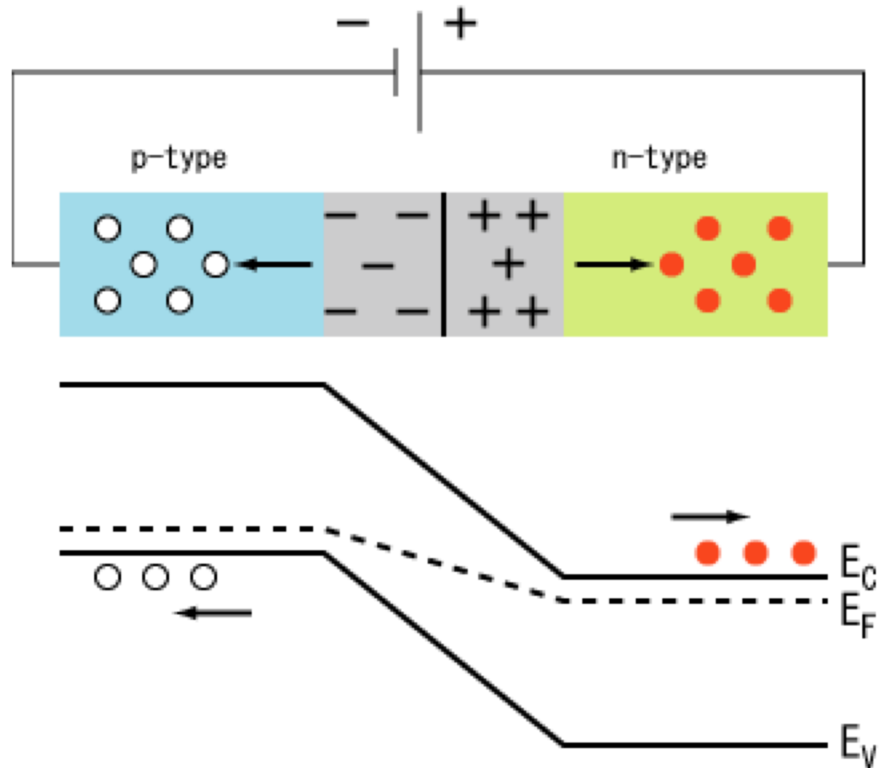


Semiconductor detectors

- La structure de base d'un détecteur semi-conducteur est une jonction biaisée inversement
- Quand 2 semi-conducteurs de types différents (n ou p) entrent en contact
  - Sous effet de diffusion une zone sans porteurs de charge est crée au point de contact
  - Forme une zone de déplétion à la jonction
  - Une barrière de potentiel se forme dans cette zone
    - Empêche la conduction entre les deux semi-conducteurs
  - L'application d'une tension inverse ($V_n > V_p$) élargi la zone de déplétion
    - Augmente l'efficacité de détection
    - C'est la base aussi des diodes

Semiconductor detectors





Jonction PN sans tension
(en équilibre)

Jonction PN en polarisation inverse

Semiconductor detectors

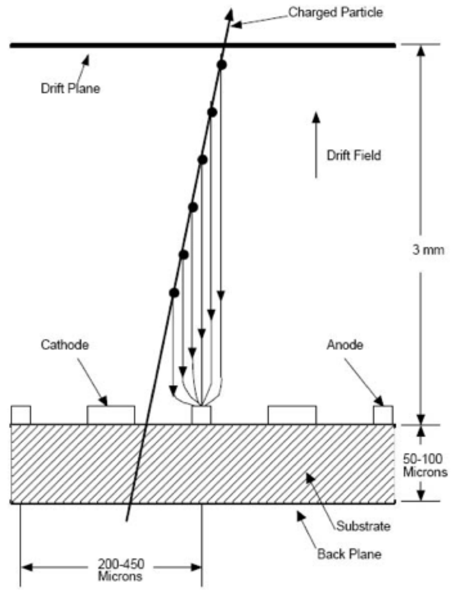
- Les caractéristiques des détecteurs semi-conducteurs
  - Efficacité
  - Linéarité
  - Courant de fuite
  - Temps de montée
- Efficacité
  - ~3 eV sont nécessaires pour créer une paire d'électrons-trous
  - 10 fois plus sensible qu'un gaz
  - 100 fois plus sensible qu'un scintillateur
  - Donc meilleure résolution en énergie comme plus d'ionisations primaires donc moins de fluctuations de charge
- Linéarité
  - Seuil de perte d'énergie est très faible
    - Donc bonne linéarité
  - Pour des particules fortement ionisées (ions lourds, Pb au LHC)
    - L'efficacité de collection est affectée par l'effet de charge spatiale
      - Les charges dérivent moins vite, donc plus de recombinaisons (le champ E est diminué)

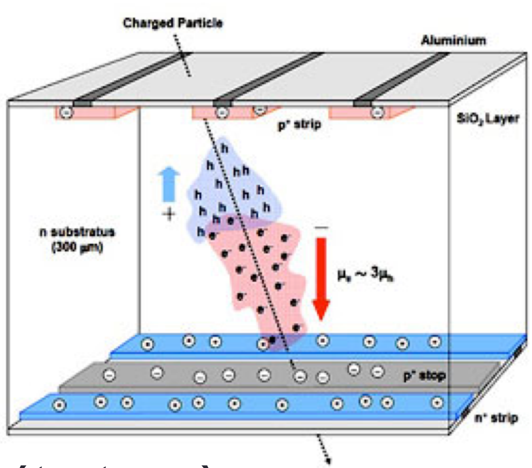
Semiconductor detectors

- Courant de fuite
  - Même si la jonction est en polarisation inverse
    - Petit courant (~ ηA) à travers la jonction
  - Le courant de fuite viens des mouvements des porteurs de charge minoritaires, des effets des impuretés et des effets de surface
- Temps de montée
  - Très rapides!
  - Le temps de montée des charges induites est de l'ordre du ~ns

Semiconductor detectors

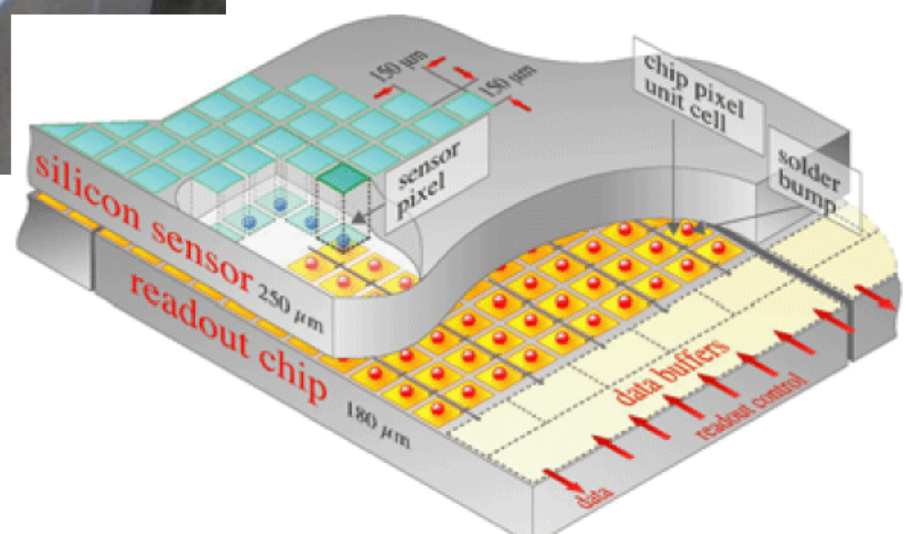
- Applications
  - Pour mesurer l'énergie
    - Excellente résolution
    - Mais limité dans l'épaisseur de la zone de déplétion (~mm) et la taille maximale des semi-conducteurs qu'on peut produire (~10 cm^2)
  - Pour mesurer la position de particules chargées
    - Profite des développements de la technologie microélectronique pour fabriquer des formes précises sur le cristal
    - Détecteurs à microbandes (e.g. ATLAS SCT)
    - Détecteurs à pixels (utilsés pour la première fois au LHC)
    - CCD ('charge coupled device')



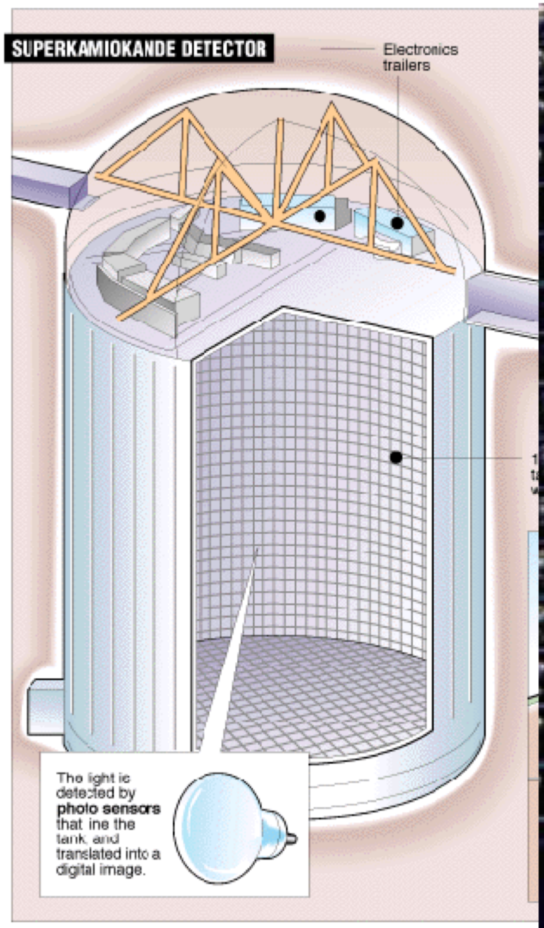


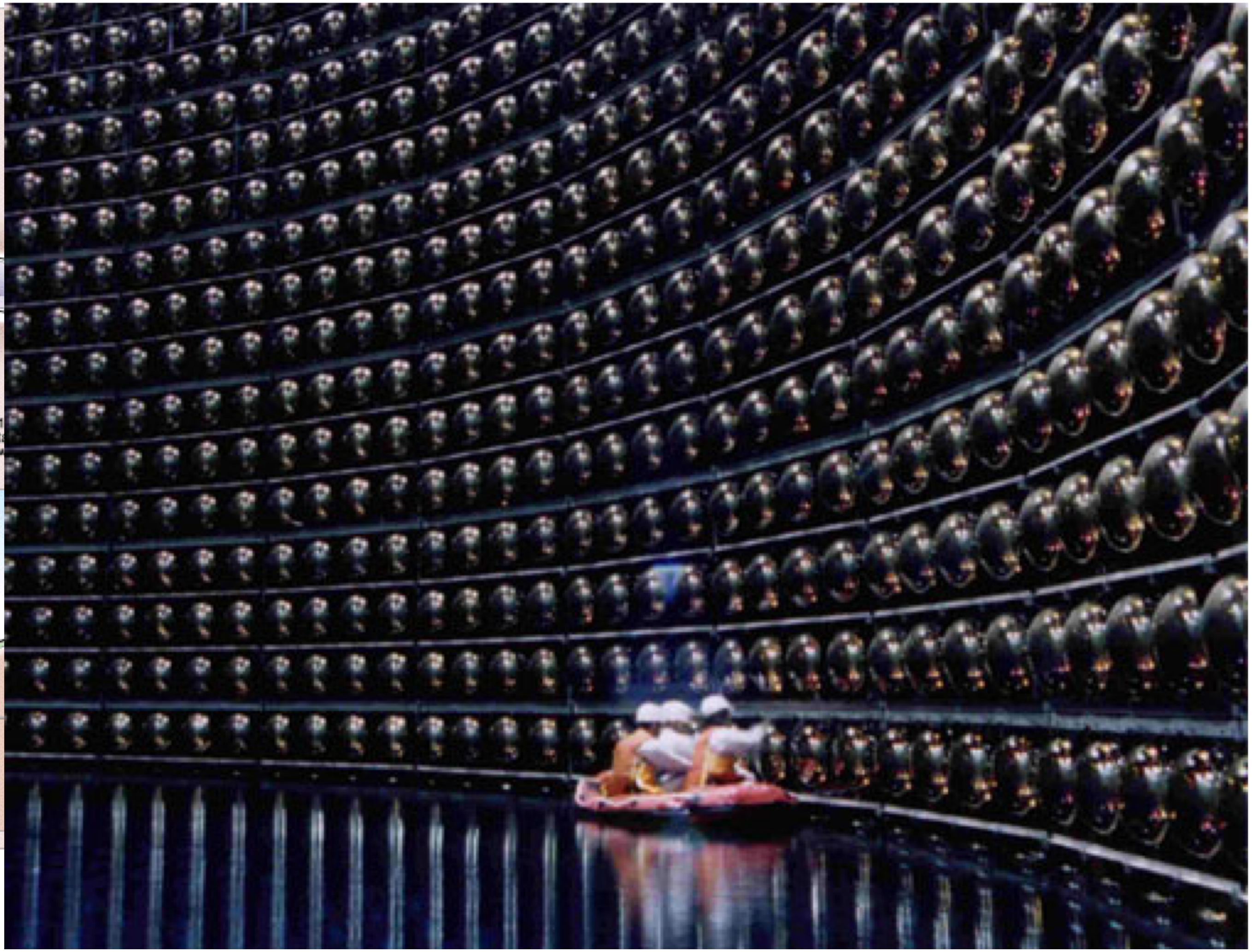
Détecteur à microbande AMS2

Semiconductor detectors



Cherenkov Detectors

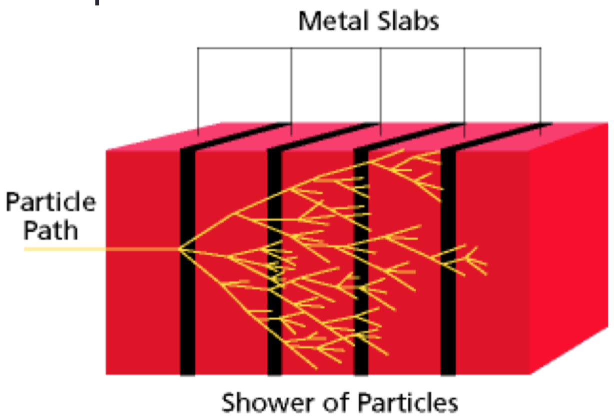




Super-Kamiokande

Calorimeters

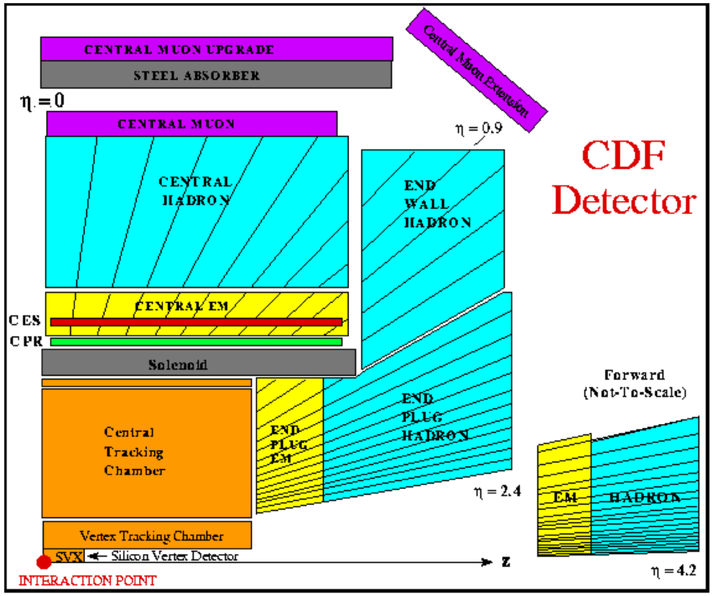
- But
  - Détecter et mesurer l'énergie des particules par absorption
  - Une segmentation spatiale pour savoir où est la particule incidente
- Principe d'opération
  - La particule incidente initie une gerbe de particules dans le détecteur
    - La forme, taille et composition de la gerbe dépend de la particule incidente et des matériaux utilisés
  - L'énergie est déposée sous forme de
    - Chaleur
    - Ionisation
    - Excitation
    - Radiation de Cherenkov
    - …



  - Différents types de détecteurs utilisent ces signaux de manière différentes
  - Le signal obtenu dépend de l'énergie totale déposée par la particule dans le milieu actif du détecteur

Calorimeters

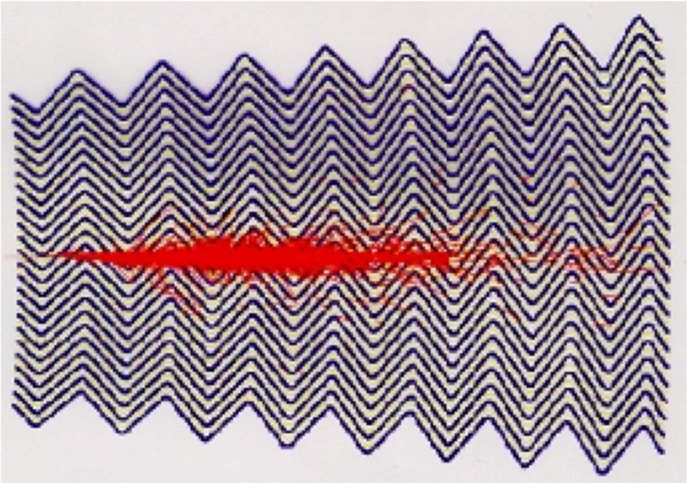
- Peuvent être construits sur presque tout l'angle solide autour de la collision (4π)
- Mesurent l'énergie de particules chargées et neutres
  - Pour autant qu'elles interagissent sous la force EM ou forte
- Une segmentation en profondeur permet une séparation entre les hadrons et les particules qui n'interagissent qu'avec la force EM
  - Souvent 2 calorimètres
    - Calorimètre EM
    - Calorimètre hadronique



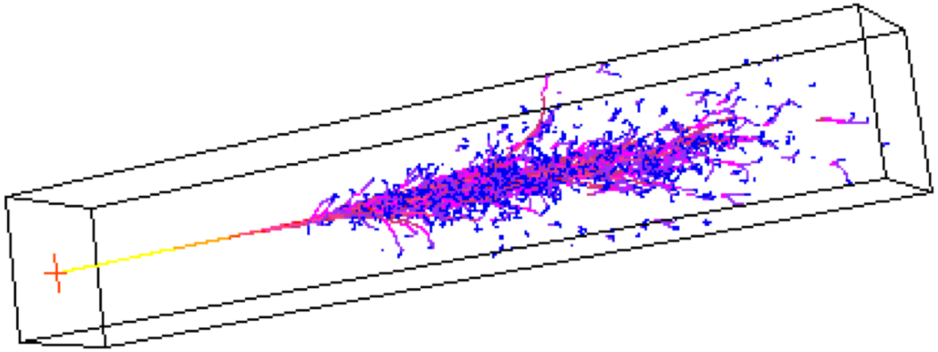
CDF

Calorimeters

- Les gerbes EM (voire sous-chapitre précédent) sont caractérisées par
  - La longueur de radiation X_0
  - L'énergie critique: E_c
  - La taille transverse
    - Rayon de Molière: $R_M = 21$ MeV / E_C



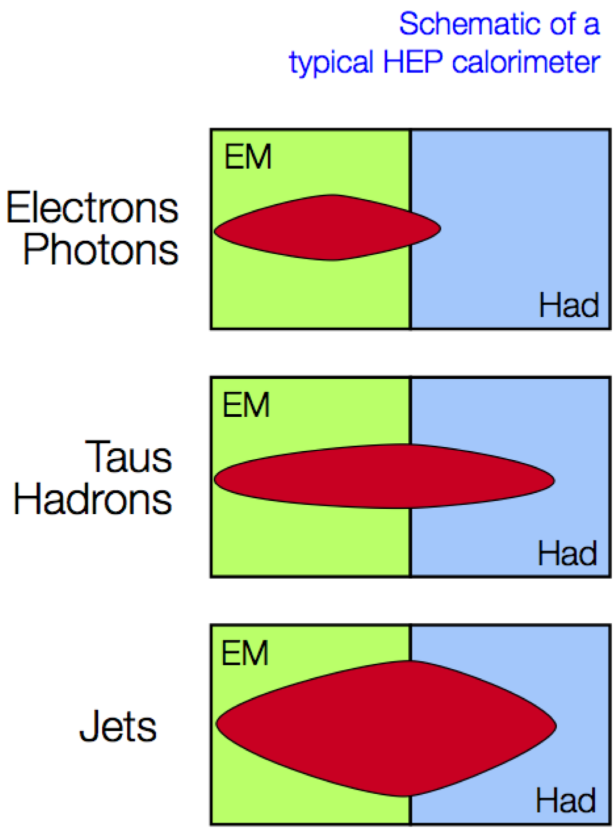
ATLAS



CMS

Calorimeters

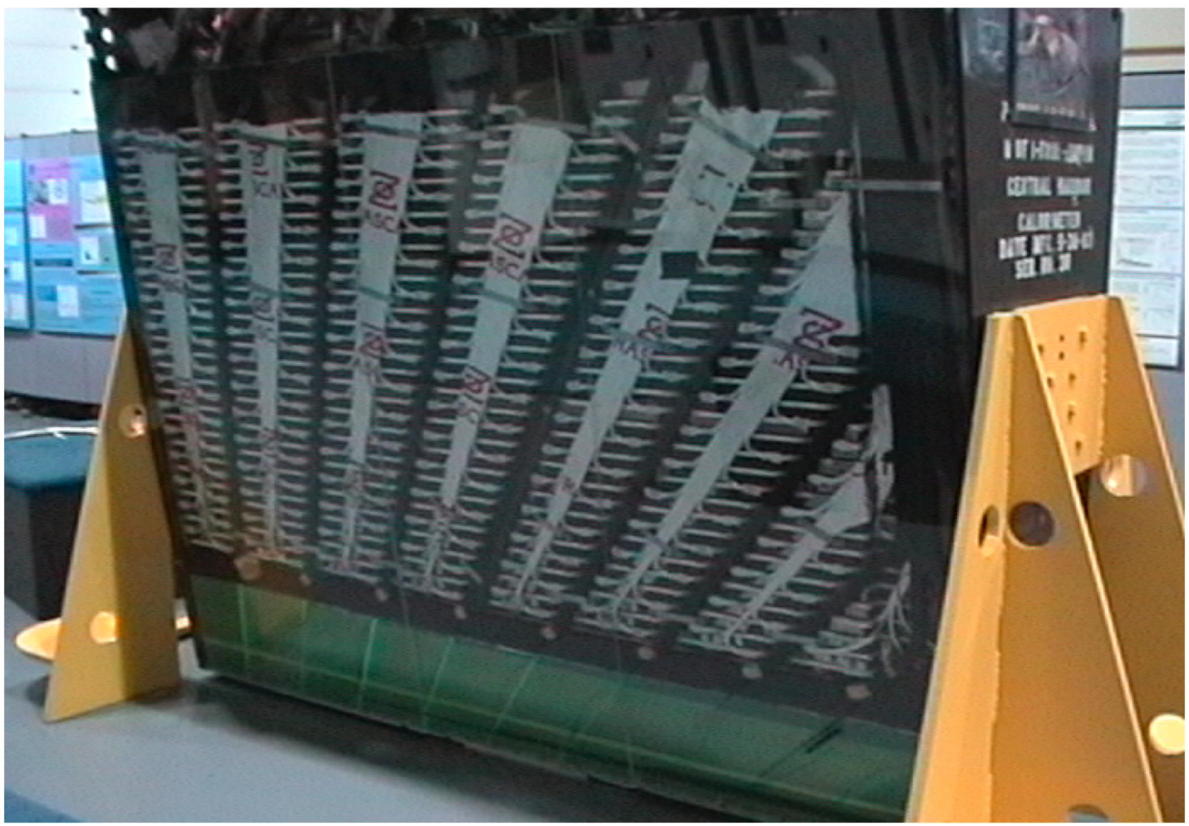
- Les gerbes hadroniques (voire sous-chapitre précédent) sont caractérisées par
  - La longueur d'absorption nucléaire λ_{nucl} (>> X_0)



	λ_{int} [cm]	X_0 [cm]
Szint.	79.4	42.2
LAr	83.7	14.0
Fe	16.8	1.76
Pb	17.1	0.56
U	10.5	0.32
C	38.1	18.8

Calorimeters

- Les calorimètres hadroniques sont souvent des ‘sampling calorimeters’
  - Alternance de couches actives et de matière passive
  - On ne mesure qu’une fraction de l’énergie totale des particules
    - Calibration nécessaire pour compenser pour l’énergie absorbée par la matière passive



Hadronic showers

- Dans une collision produisant des hadrons
  - Prenons l'exemple d'une interaction produisant une paire de quarks
  - La force forte est forte
    - Production non-pas d'un seul hadron mais d'une gerbe de hadrons
  - Les hadrons chargés seront observés dans le traceur
  - Le hadrons neutres et chargés vont former des gerbes hadroniques dans le calorimètre
  - On doit alors utiliser des algorithmes compliqués pour reconstruire au mieux quelles dépôts d'énergie viennent de la même gerbe de hadrons ou de la même particule initiale
    - 'jet algorithms' (MidPoint, AntiKt,..)