Interaction particle-matter at high energy. An example

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- Detectors played a key role in physics since 1900

- Four detectors have been distinguished:
  - Cloud chamber (C. Wilson, Nobel prize in 1927 and Patrick Blackett, Nobel prize in 1948)
  - Bubble chamber (D. Glaser, Nobel prize in 1960)
  - Wire chamber (G. Charpak, Nobel prize in 1992)
  - CCD (Willard Boyle and George Smith, Nobel prize in 2009)

- Implies nuclear physics, thermodynamics, condensed matter, chemistry, optics, …

Sources and references

- « Particle Detectors », C. Grupen and B. Schwartz, 1996
- CERN Summer Student Lectures
  - In particular « Particule Detectors », C. Joram (2002)

Typical numbers

- Distances:
  - In 1 ns, a particle with $v = c$ moves by 30 cm
  - In 1 μs, an ionization electron moves 5 cm in a gaz
  - In 1 ms, a proton runs 11 times around LHC (11x27 ≈ 300 km) and an ion moves 5 cm in a gaseous detector

- Lifetime / distance:

	Muon	Pion	Méson B
Lifetime	2,2 μs	26 ns	1 ps
Distance	660 m	7,8 m	300 μm

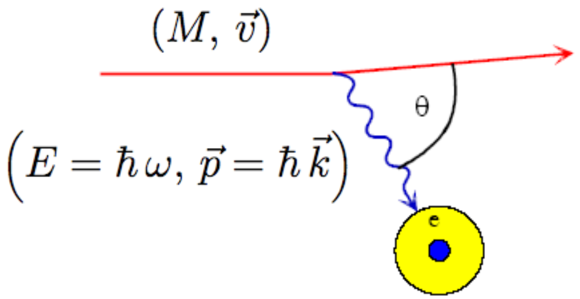
  - Within a detector, muons are stable, B mesons will not be seen before their decay

Plan

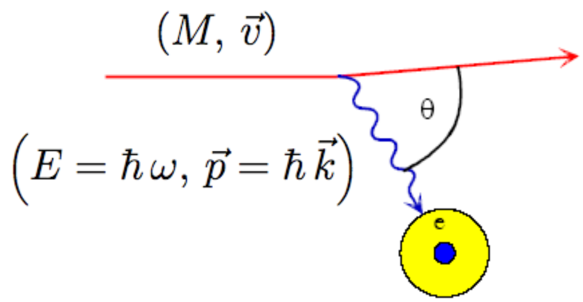
I. Interaction particle-matter
   1) Heavy charged particles
   2) Light charged particles
   3) Photons
   4) Neutrinos

II. An example: charged tracks reconstruction

- We consider here heavy particles with $m > m_\mu \approx 200\, m_e$ (ie everything but electrons) : $\mu^\pm$, $\pi^\pm$, α, p, ..



- At low energy, heavy particles loose energy in matter via collisions with the atomic electrons of the target by photon exchange:
  - Excitation of the atom
  - If $\hbar\omega$ is large enough, ionization can occur
  - Ionization electrons have sometimes enough energy to ionize other atoms (δ electrons)
  - In some cases, the photon can escape instead of ionizing (Cherenkov effect and transition radiation)



- Collisions with the nucleus are negligeable (m_e « m_{Noy}) as long as the energy is not too high

- « collision » is to be taken with quantum mechanics meaning and not classical one
  - Nothing to do with collision of two cars but has to be seen as an interaction

- The relevant parameter to characterize the collision is the impact parameter (minimum distance between two particles)

- Cross section is very small ($\sigma \approx 10^{-16}$-10^{-17} cm^2) but the number of atoms is very high ($N_A \approx 10^{23}$ atoms/cm^3)
  - A 10 MeV proton looses all its energy in 250 μm of copper

- The number of interaction is controlled by statistics:
  - $\Rightarrow$ relative fluctuations very small
  - In practice, we observe a continuous decrease of the energy down to the thermal kinetic energy
  - We use the mean energy loss per unit length:

$$\left\langle \frac{dE}{dx} \right\rangle$$

- Relativistic quantum mechanics gives the Bethe-Bloch formula which describe the average energy loss by ionization:

$$\left\langle \frac{dE}{dx} \right\rangle = -4\,\pi\,N_A\,r_e^2\,m_e\,c^2\,\frac{Z}{A}\,\frac{z^2}{\beta^2}\left[\ln\left(\frac{2\,m_e\,c^2\,\gamma^2\,\beta^2}{I^2}\right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

- Validity domain:
  - As soon as the speed of the incoming particle is > speed of the atomic electrons $\beta_{min} = \frac{v}{c} \approx 0.01$
  - As long as the Bremsstrahlung (see later) does not dominate:
    - For muons, it means $E < 1$ TeV

$$\left\langle \frac{dE}{dx} \right\rangle = -4\,\pi\,N_A\,r_e^2\,m_e\,c^2\,\frac{Z}{A}\,\frac{z^2}{\beta^2}\left[\ln\left(\frac{2\,m_e\,c^2\,\gamma^2\,\beta^2}{I^2}\right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$

- Constants: N_A, r_e, m_e, Z, A

Avogadro — Classical radius and mass of the e- — Charge and atomic mass of the target

$$N_A \approx 6,02\ 10^{23}\ \mathrm{mol}^{-1} \qquad r_e = \frac{e^2}{4\,\pi\,\epsilon_0\,m_e\,c^2} \approx 2,8\ \mathrm{fm} = 2,8\,10^{-15}\ \mathrm{m}$$

- Dependences:
  - Does not depend on the mass of the incoming particle but only on its charge z and its velocity β !
  - Depend upon the target via Z, A, I, δ et C (constants)
- N_A is expressed in mol^{-1}, r_e in cm, $m_e c^2$ in MeV, A in g/mol

$$\left\langle \frac{dE}{dx} \right\rangle \Rightarrow \text{expressed in MeV g}^{-1}\text{ cm}^2$$

$$K = 4\pi N_A r_e^2 m_e c^2 \approx 0,307 \text{ MeV g}^{-1}\text{cm}^2$$

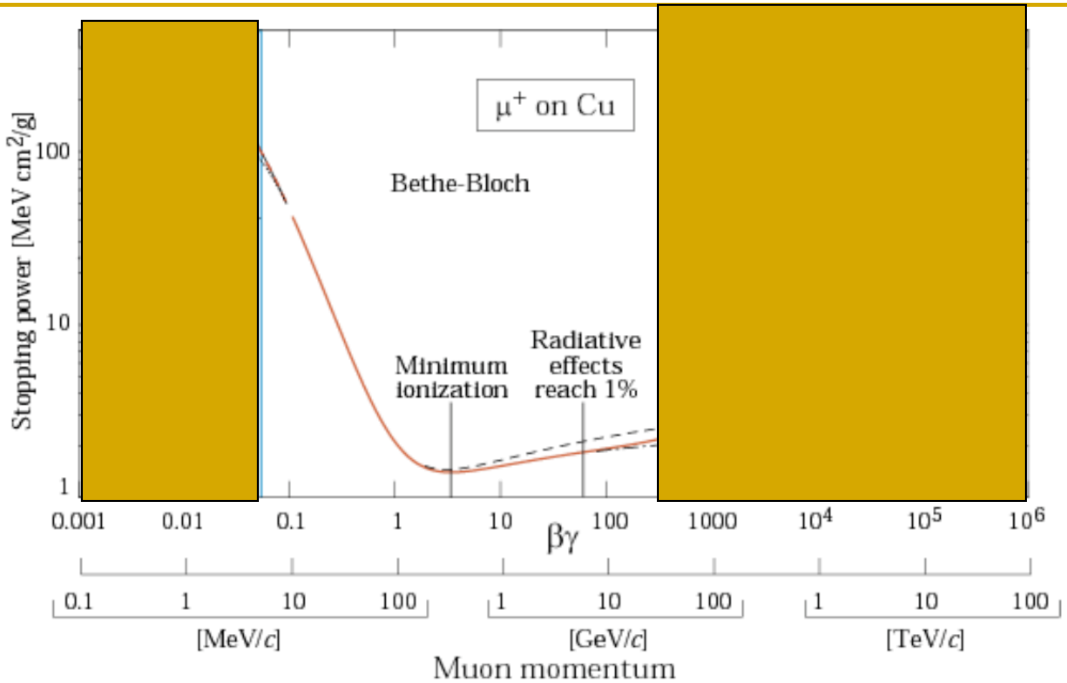
- We set:

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

  - Precision of several % from several MeV ($\beta \approx 0{,}1$) up to several tens of GeV

- $dx = \rho \, dl$ is the surface density (ρ: density in g/cm^3)

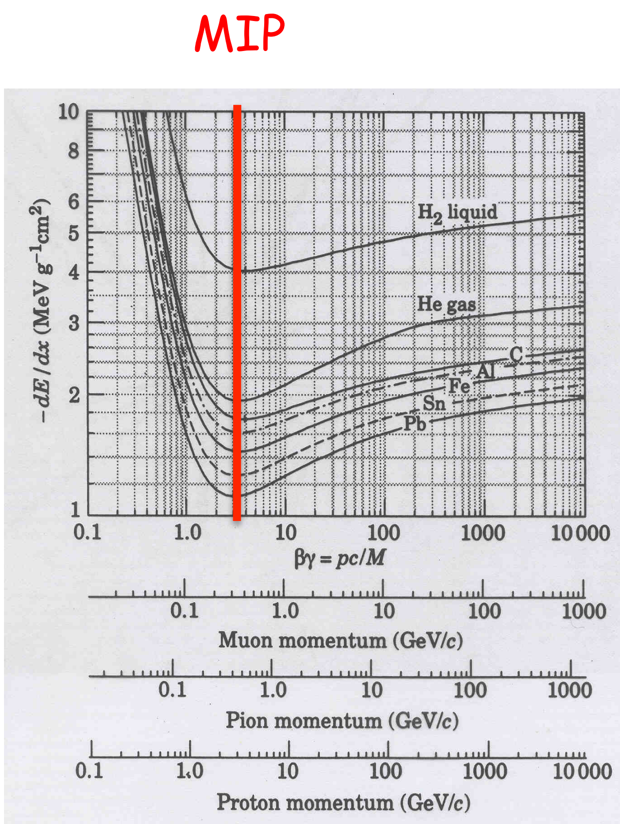
- From now on, we will write $\frac{dE}{dx}$ and no longer $\left\langle \frac{dE}{dx} \right\rangle$



Energy deposited by muons in copper as function of $\beta\gamma$

- *dE/dx* decreases like $\beta^{-5/3}$ for $\beta\gamma < 3$
- *dE/dx* has a minimum for $\beta\gamma \approx 3{,}5$ (Minimum Ionizing Particle or MIP) for which $\langle dE/dX \rangle \approx 1 - 2$ MeVg^{-1}cm^2
- After the minimum, $\langle dE/dx \rangle$ increases as $\ln(\gamma^2)$

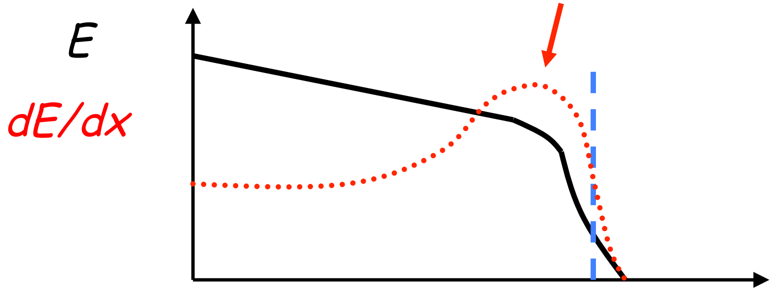
- Position and value of the minimum do not depend upon the particle
  - *dE/dx* ≈ 1 – 2 MeV g^{-1} cm^2
- Curves are different for various particles because of the β variation (for *p* constant)
- Real detectors do not measure *dE/dx* but deposited energy *ΔE* in width *Δx*

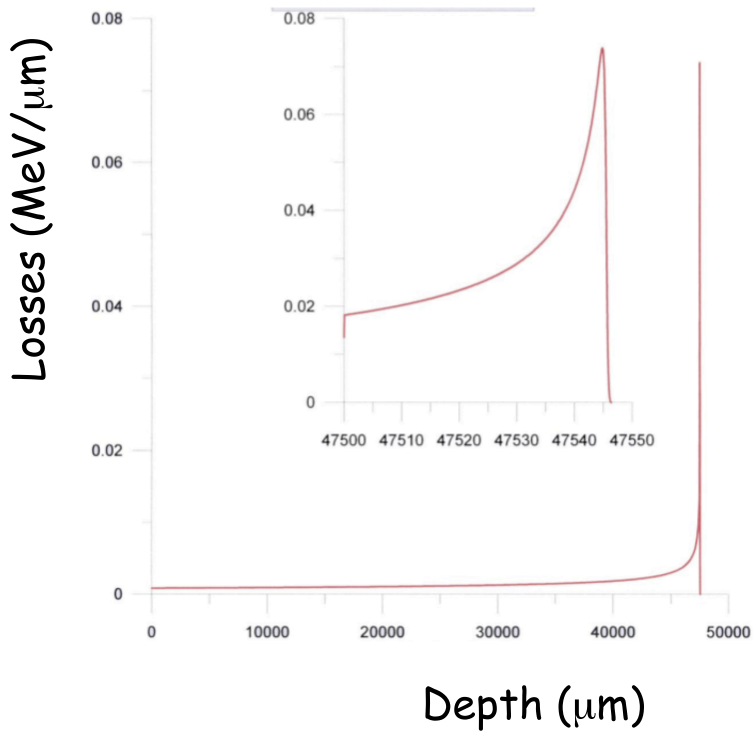


Energy deposited by muons in several media as function of βγ

- Typical Bragg curve (relation between distance in the material and dE/dx)

Speed decrease due to the dE/dx increase as $\beta^{-5/3}$





Bragg curve for 70 MeV protons in water

- Used in hadron therapy or proton therapy

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II. An example: charged tracks reconstruction

- Electrons or positrons first

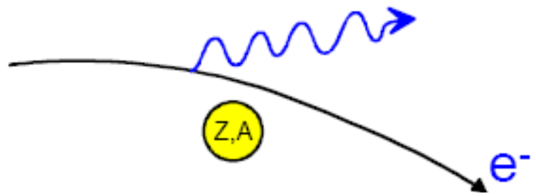
- Bethe-Bloch formula must be modified because the incoming particle is the same one as the target

$$\frac{dE}{dx} = -K \frac{Z}{A\,\beta^2} \left[\ln\left(\frac{m_e\, c^2\, T\, \sqrt{T+2}}{I\,\sqrt{2}} \right) + \frac{f(T)}{2} - \frac{\delta}{2} \right]$$

  - where T is the incoming particle cinetic energy (in units of $m_e c^2$) and $f(T)$ another function (not the same one for electrons and positrons)

A new mechanism

- A light particle will radiate a real photon in the field of a nucleus



Bremsstrahlung

  - Only apply for $e^\pm$ (and μ with energy > 1 TeV)
  - For $e^\pm$:

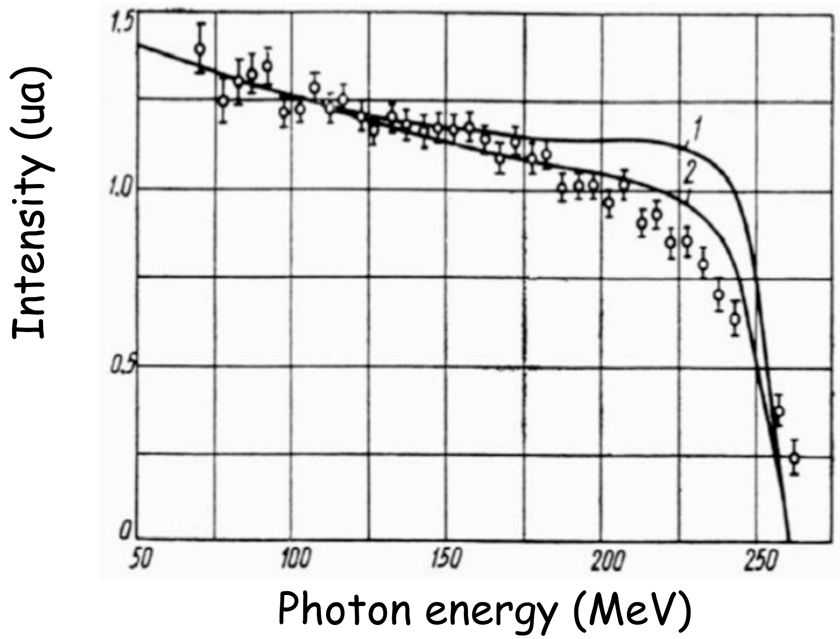
$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad X_0 = \frac{A}{4\,\alpha\,N_A\,Z^2\,r_e^2\,\ln\left(\frac{138}{Z^{1/3}}\right)}$$

  - Proportional to E: dominates at high energy
  - Introduced radiation length X_0 (g/cm^2)
  - Relationship between radiation lengths in g/cm^2 and in cm is:

$$X_{0\,[g/cm^2]} = \rho_{[g/cm^3]}\,X_{0\,[cm]}$$

An example

Bremsstrahlung spectrum for 260 MeV electrons on 0.5 mm tungsten



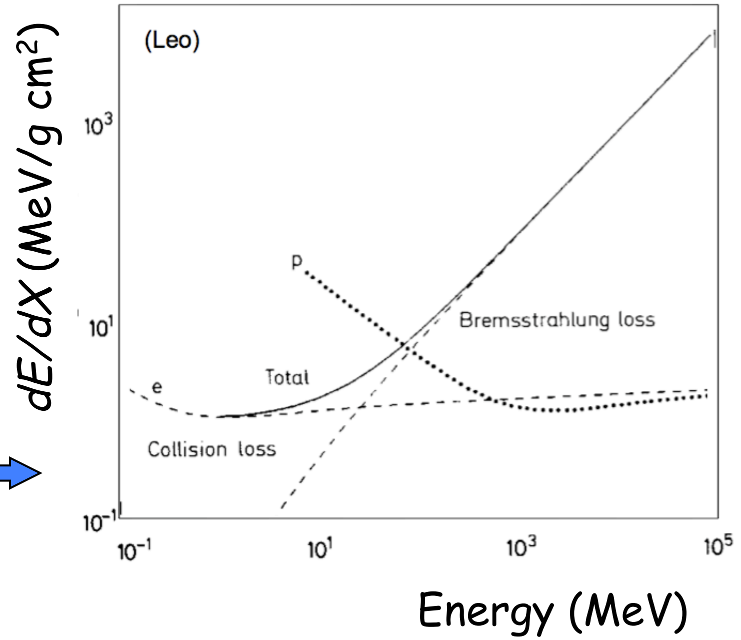
- A large part of the energy (up to ≈ 100% !) can be taken by bremsstrahlung photons
  - ⇒ huge fluctuation on the path in matter

Total losses

- Finally:

$$\left.\frac{dE}{dx}\right|_{Total} = \left.\frac{dE}{dx}\right|_{Ionisation} + \left.\frac{dE}{dx}\right|_{Bremsstrahlung}$$

Energie loss by e± and p in copper



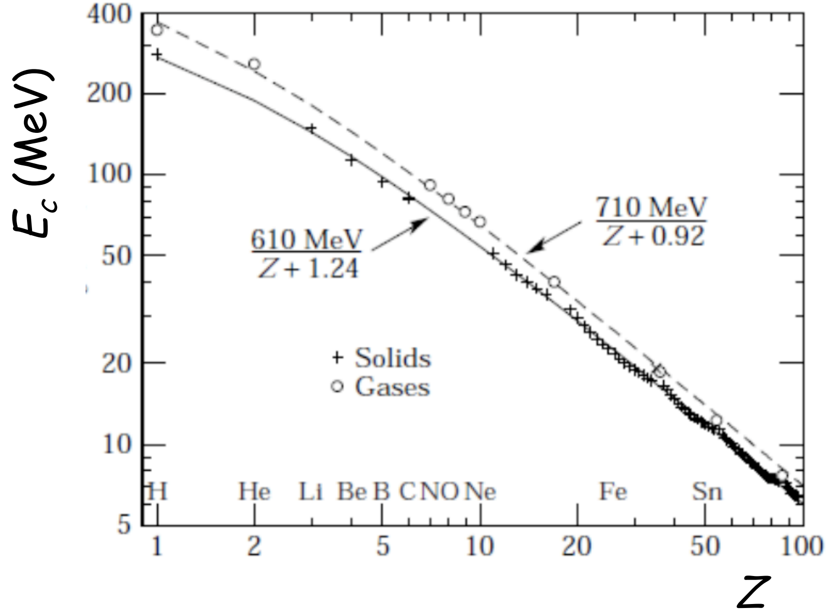
Critical energy

- By definition, critical energy is the energy where ionization and bremsstrahlung losses are equal
- For $e^\pm$:

$$E_c^{Sol+Liq} \approx \frac{610\ \mathrm{MeV}}{Z+1,24}$$

$$E_c^{Gaz} \approx \frac{710\ \mathrm{MeV}}{Z+1,24}$$

Density effect in *dE/dx* (ionization)



Bremsstrahlung for heavy particles

- Incoming particle with mass *m* and charge *ze*:

$$\left.\frac{dE}{dx}\right|_{Rayonnement}(m,\, z) \;=\; \left(\frac{m_e}{m}\right)^2 z^2 \left.\frac{dE}{dx}\right|_{Rayonnement}(e^-)$$

- For $\mu^{\pm}$, this translates into:

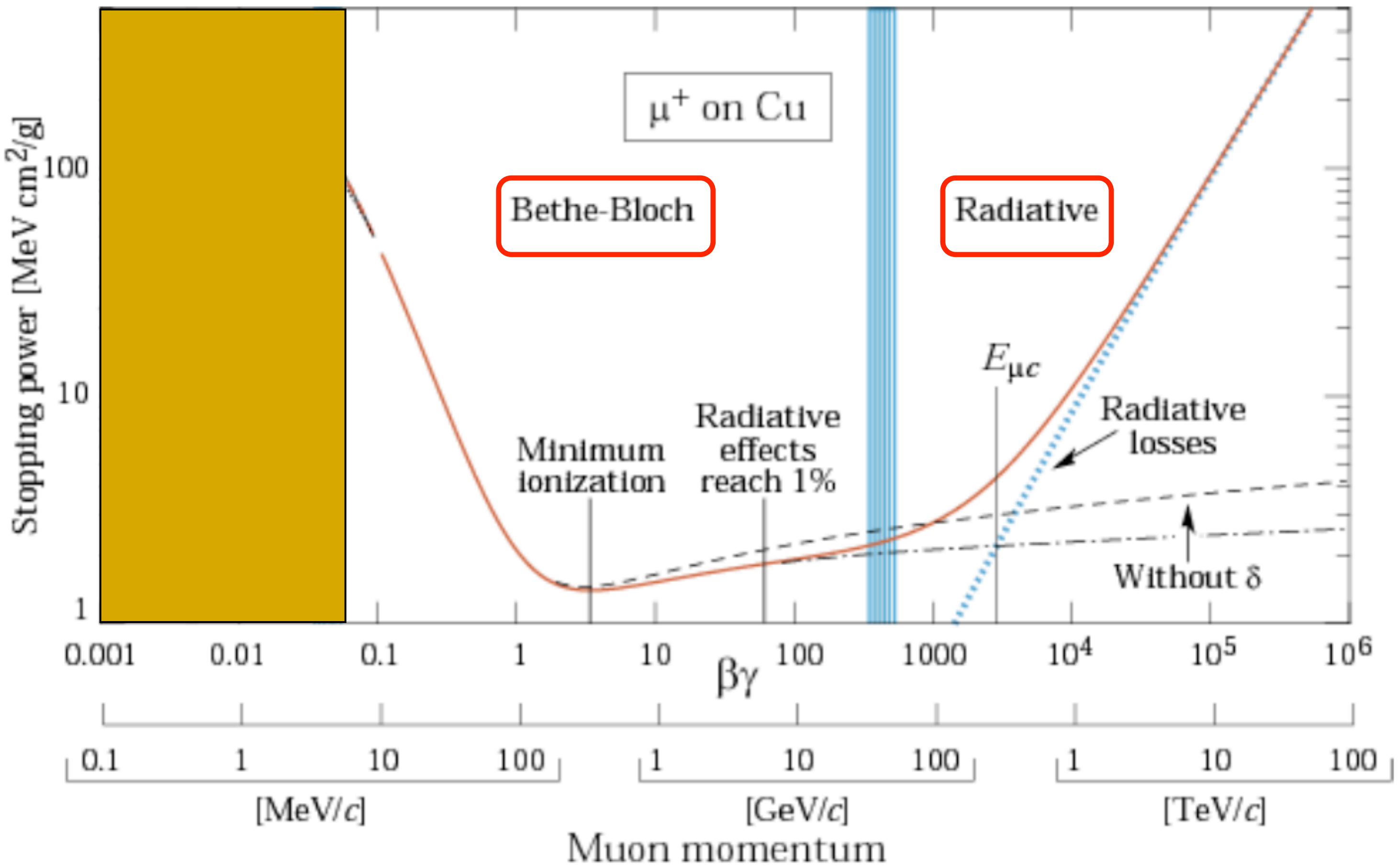
$$E_c \;\approx\; E_c^{Electron}\left(\frac{m_\mu}{m_e}\right)^2$$

- Example for iron (Z = 26) :

$$E_c(e^-) \;=\; 22,4 \text{ MeV} \qquad \text{et} \qquad E_c(\mu) \;=\; 1 \text{ TeV}$$

We now understand fully the *dE/dx* curve

Energy deposited by muons in copper



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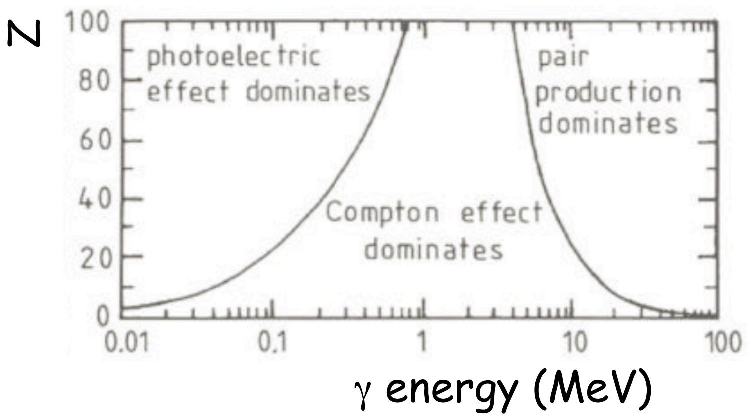
II. An example: charged tracks reconstruction

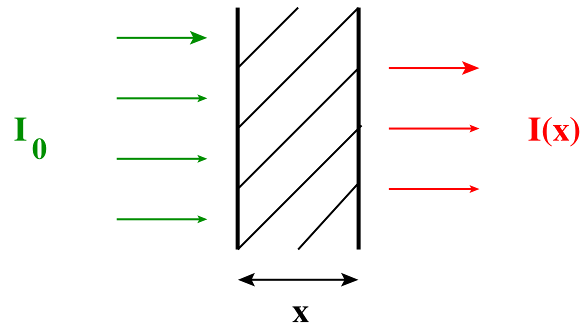
Interaction of photons with matter

- To be detected, a γ must create charged particles or transfer energy to a charged particle. Several possible effects:
  - Photoelectric effect (dominant for E_γ < 100 keV)
  - Compton diffusion (dominant for $E_\gamma \approx 1$ MeV)
  - Pair production (dominant for E_γ > 1 MeV)



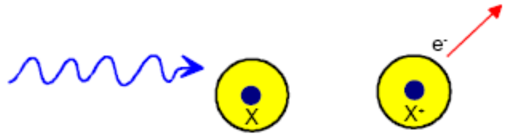
- In each case, the γ is absorbed or elastically scattered. They keep their energy but the beam intensity decreases
- Attenuation μ is defined by:

$$I(x) = I_0 \exp(-\mu x)$$



Photoelectric effect

- Mechanism: γ + atom → atom$^+$ + e$^-$



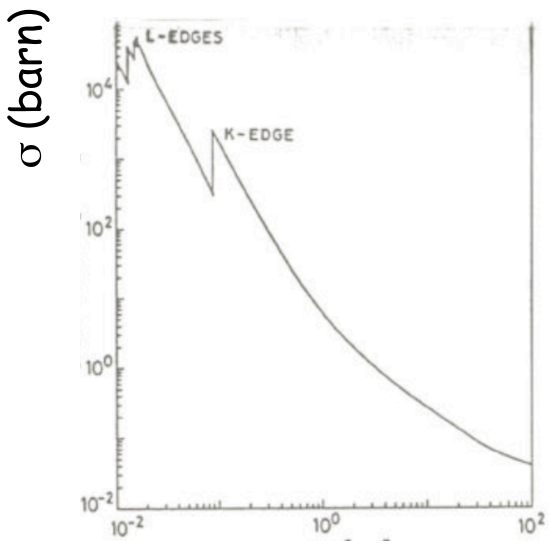
- Deal with K shell e$^-$

- Cross section

$$\sigma_{Photo} \approx 4\sqrt{2}\,\alpha^4 Z^5 \left(\frac{m_e c^2}{E_\gamma}\right)^{7/2} \sigma_{Th}$$

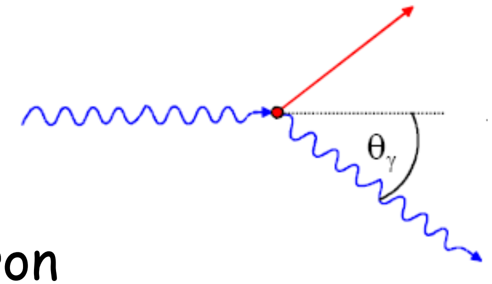
Thomson cross section

$$\sigma_{Th} = \frac{8}{3}\pi r_e^2 \approx 665 \text{ mb}$$



- Remember: 1 mb = 10^{-24} cm^2

Compton diffusion



- Mechanism: $\gamma + e \rightarrow \gamma' + e'$
  - Scattering of a photon on a quasi free electron

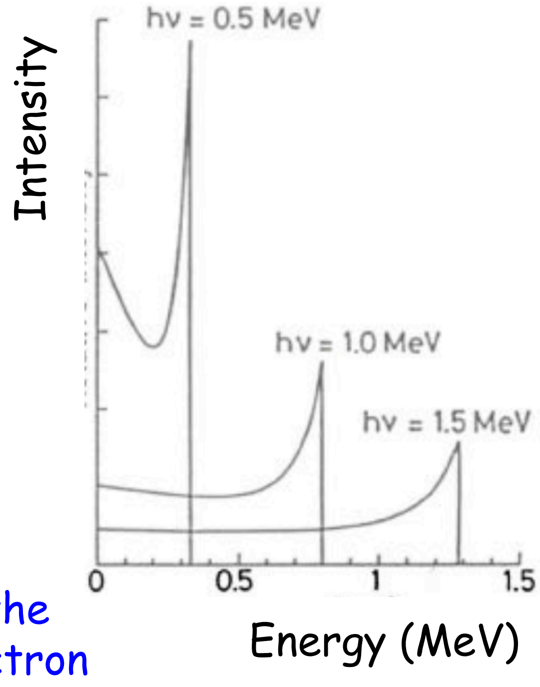
- Energy:

$$E'_\gamma = \frac{E_\gamma}{1 + \epsilon\,(1 - \cos(\theta_\gamma))} \qquad \epsilon = \frac{E_\gamma}{m_e\,c^2}$$

- Cross section:

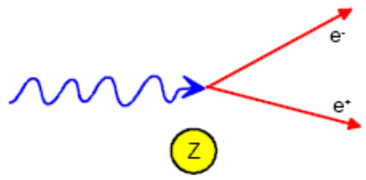
$$\sigma_c^e \approx \frac{\ln(\varepsilon)}{\varepsilon} \quad \text{et} \quad \sigma_c^{atome} \approx Z\,\sigma_c^e$$

  - Decrease when photon energy increase



Pair creation

- Mechanism: γ + nucleus → e^- + e^+ + nucleus



- Occur in the field of a nucleus only if

$$E_\gamma > 2\, m_e\, c^2 \approx 1 \text{ MeV}$$

- Cross section at high energy (cm^2/atom) :

$$\sigma_{Paire} \approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}$$

Independant of the energy !!

- One introduces λ_{Paire}:

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

  - On average, a high energy γ converts into e^+e^- pair after 1 X_0

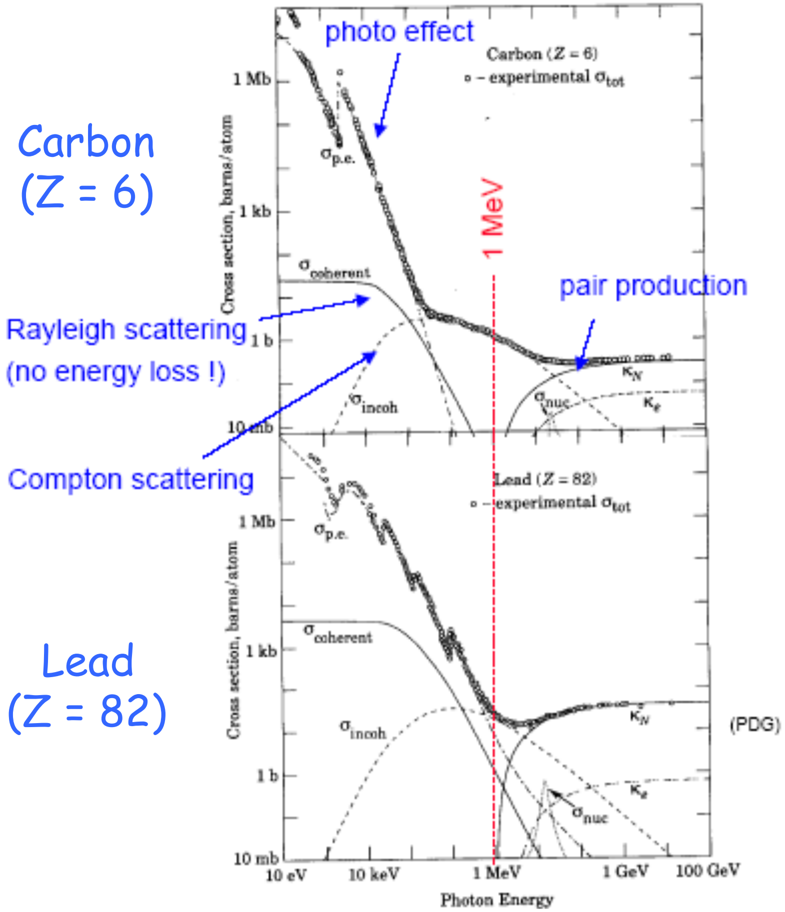
Total effect

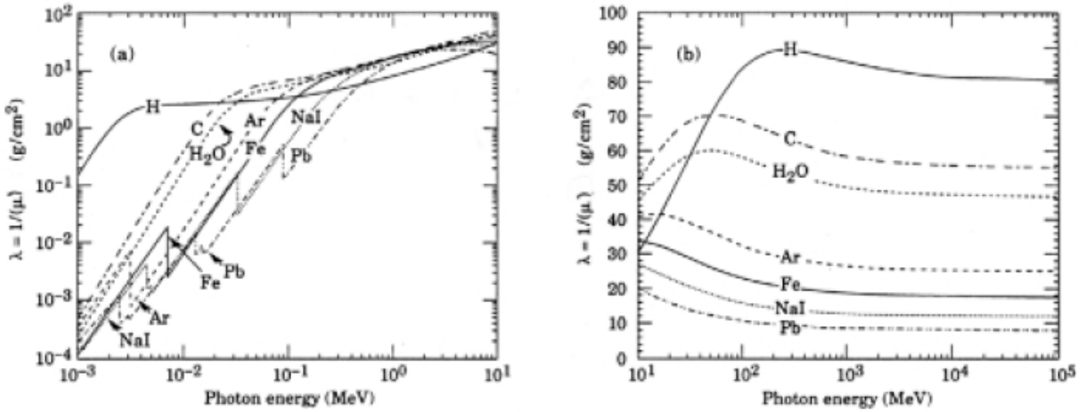
Thickness (g/cm²)

Finally, one has: $I(x) = I_0\, e^{-\mu x}$ avec $\mu = \mu_{photo} + \mu_{Compton} + \mu_{paire} +$

Attenuation coefficient (cm²/g)

$$\mu_i = \frac{N_A}{A}\,\sigma_i$$





Variation of 1/μ as fonction of the energy

Plan

I. Interaction particle-matter
   1) Heavy charged particles
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II. An example: charged tracks reconstruction

- Neutrinos are only sensitive to weak interaction
  - Very small cross sections

- To detect them, they have to interact:

$$\nu_\ell + n \longrightarrow \ell^- + p \qquad \text{avec} \qquad \ell^- = e^-, \mu^-, \tau^-$$
$$\bar{\nu}_\ell + p \longrightarrow \ell^+ + n \qquad \text{avec} \qquad \ell^+ = e^+, \mu^+, \tau^+$$

- Typically, detection efficiencies are of the order of 10^{-17} in 1 m of iron
  - Neutrino detectors are enormous and have to deal with very high fluxes

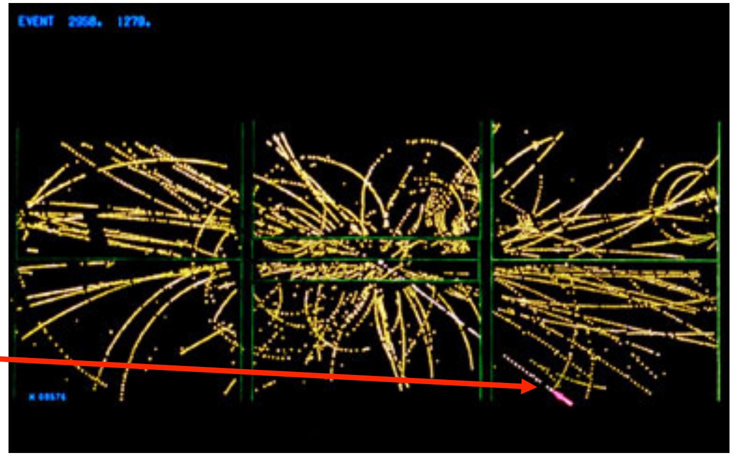
Example: UA1

- On colliders, missing energy and momentum are tagged to neutrino(s)

- Allow UA1 to reconstruct the neutrino in:

$$W^+ \longrightarrow e^+ + \nu_e$$

The positron !



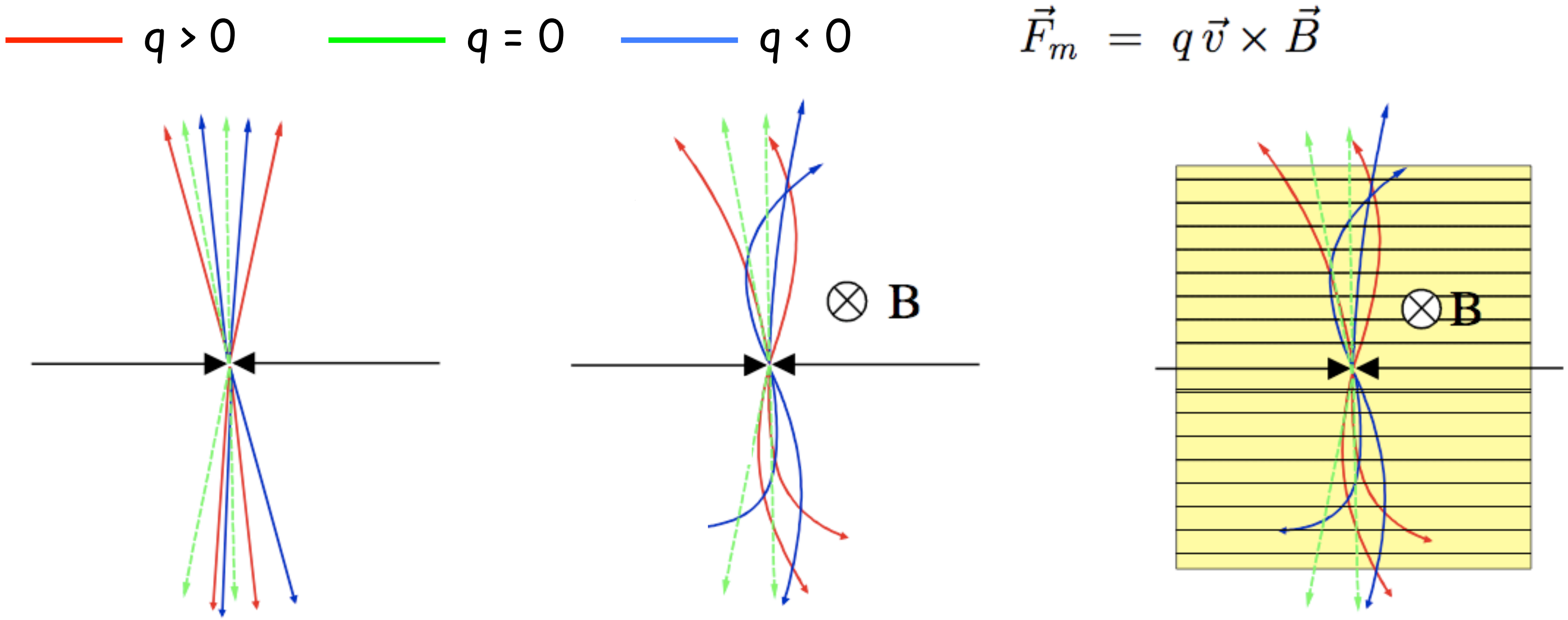
- One need a very strong commitment to theory to say this..

Plan

I. Interaction particle-matter

II. An example: charged tracks reconstruction
   1) Generalities
   2) Ionization detectors
   3) Scintillation detectors
   4) Semiconductors

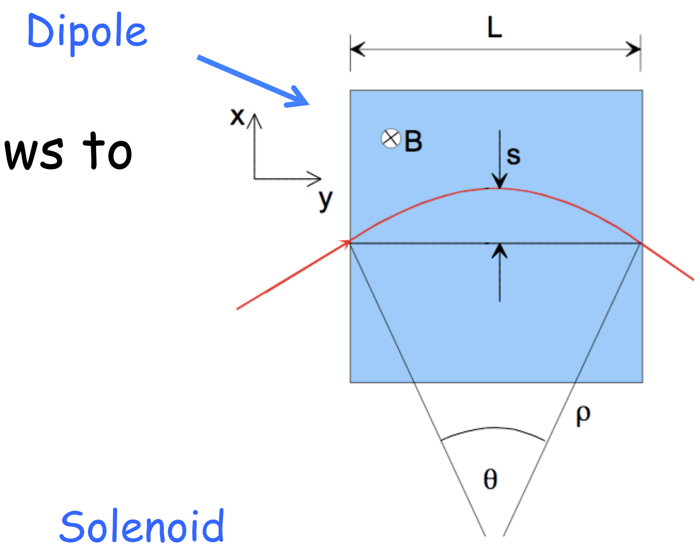
Why doing this ?



Without B | *With B* | *With B and a detector*

⇒ The sign of the charge is given by the curvature in *B* field

Momentum measurements in *B* field

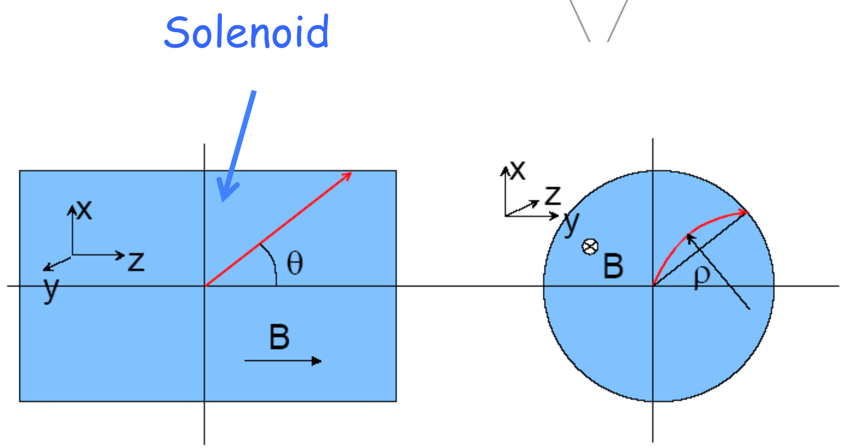


- Trajectory measurement in *B* field allows to measure p_T :

$$p_{T_{[GeV/c]}} \;=\; 0,3\, B_{[T]}\, \rho_{[m]}$$

  - Sign of curvature gives the charge

- In a solenoid, one has:



$$\left.\frac{\sigma(p)}{p}\right|_{Exp} \propto \frac{1}{\sqrt{N}}\,\frac{\sigma(x)\,p}{B\,L^2}$$

$$p_T \;=\; p\,\sin(\theta)$$

$\Rightarrow$ Increase *N* (number of measurement points) and decrease $\sigma(x)$ (position resolution)

Plan

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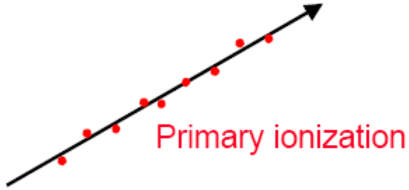
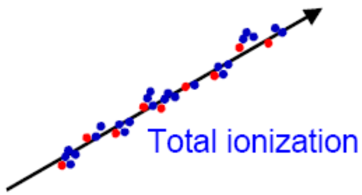
II. An example: charged tracks reconstruction
   1) Generalities
   2) Ionization detectors
   3) Scintillation detectors
   4) Semiconductors

- They detect a charged particle by measuring to total charge (electron + ion) deposited in matter
- Detector could be gas, liquid or solid
- If one does not do anything, probability of recombination is very high.
    - To get ionization electron, we need to apply an electric field

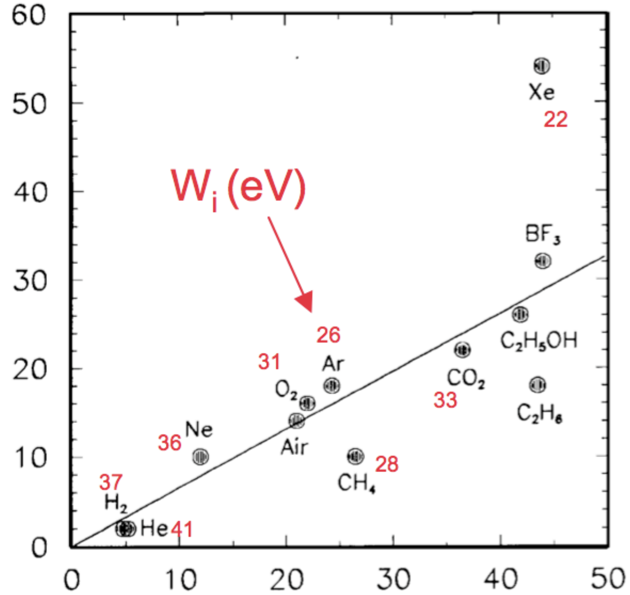
Gas ionization



- Fast particles ionize a gas. Each primary electron can sometimes ionize himself other atoms: ⇒ secondary ionization



$$\begin{cases} \Delta E : \text{Total energy loss} \\ W_i : \text{Energy loss by each electron/ion pair (typically 30 eV for a gas)} \end{cases}$$



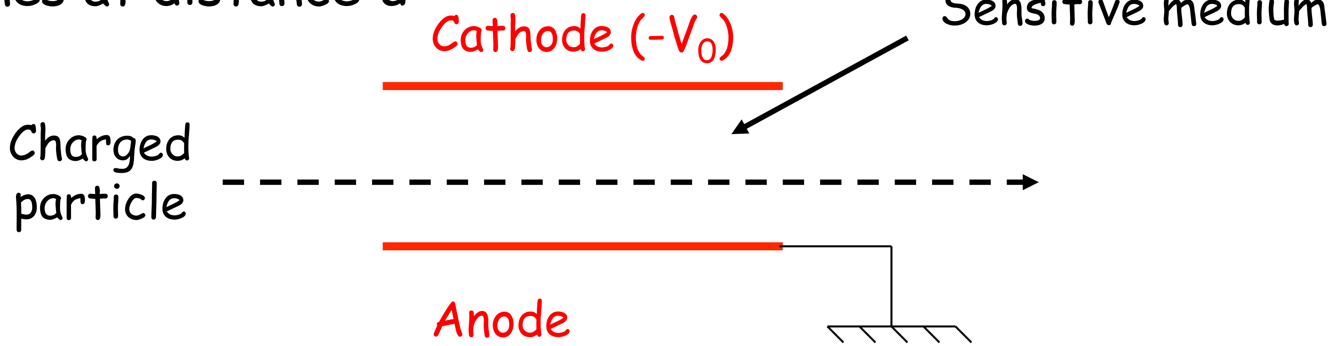
Number of initial e⁻/ion pairs in a gas

$$n_{total} = \frac{\Delta E}{W_i} = \frac{\frac{dE}{dx}\Delta x}{W_i} \approx 3 - 4\, n_{primaire}$$

- Amplification is needed because ≈ 100 e-/ion pairs is a small charge !

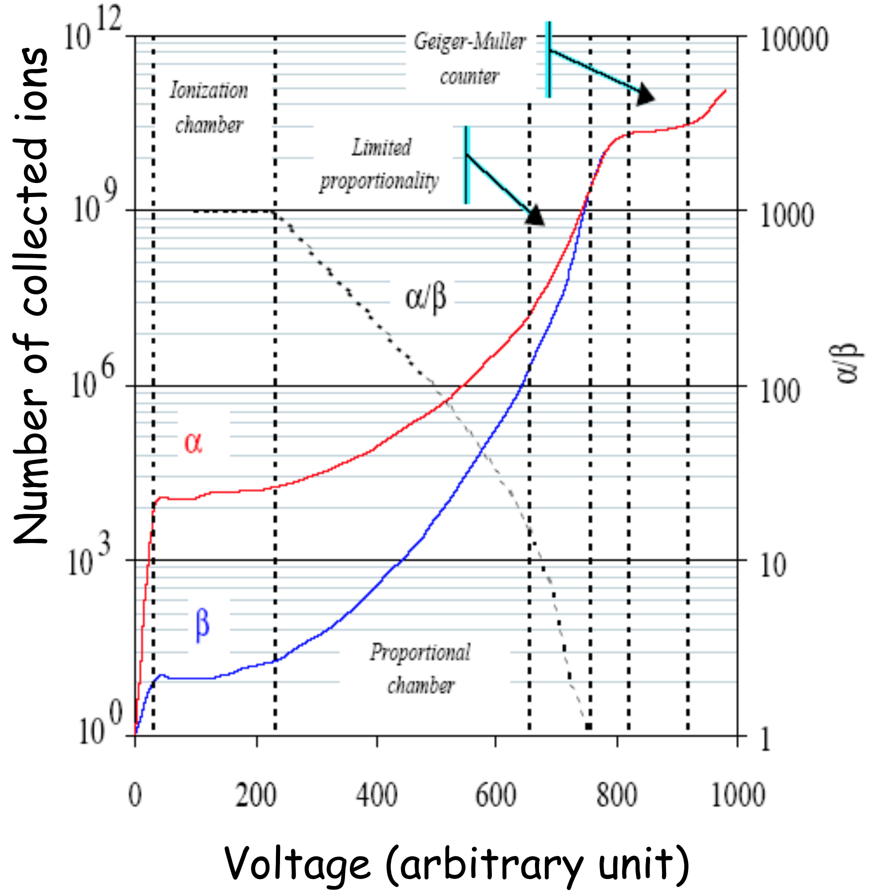
Simplest detector: ionization chamber

- 2 metallic planes at distance d



- Typical values: d = 5 cm and E = 500 V/cm
  - Δv^+ = 7,5 mm/ms and Δv^- = 5 mm/μs
- Signals are very small and require either a good electronics or a huge amplification
- Expectation: selection of gas should matter

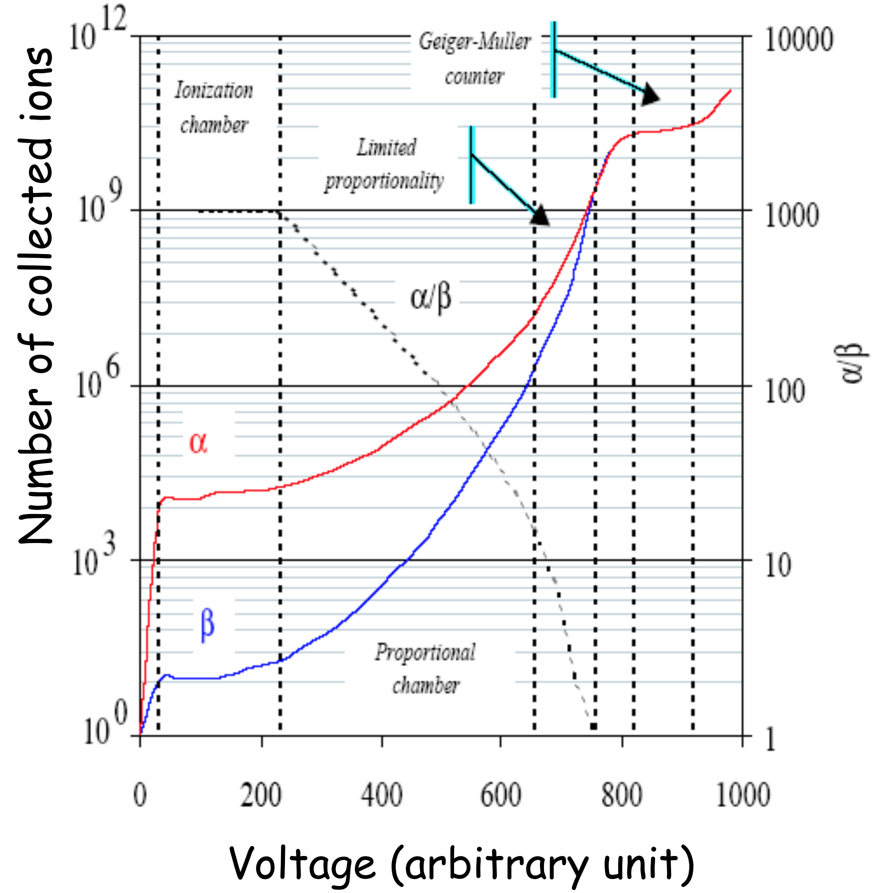
- Several types of detectors based on their physical process:
  - Recombination (no interest)
  - Ionization chamber
    - All initial charge is collected without amplification
    - Gain ≈ 1
  - Proportional counters
    - Electric field is strong enough to initiate cascade
    - Gain ≈ 10^4-10^5



Number of collected ions for α and electrons

- Saturated proportional counters
  - *E* field even higher
  - Pulsed HV
  - Gain ≈ 10^8-10^9

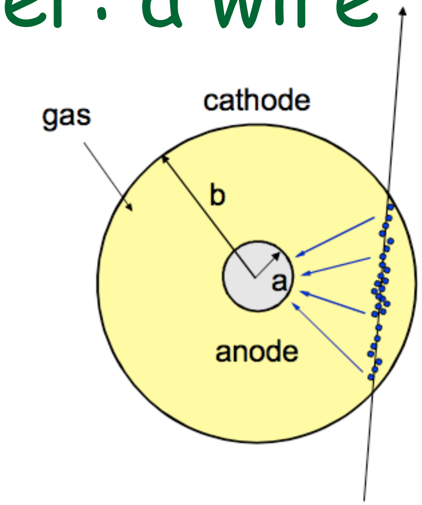
- Geiger Muller counters
  - All the anode wire is affected
  - Only way to recover is to turn off the HV



Number of collected ions for α and electrons

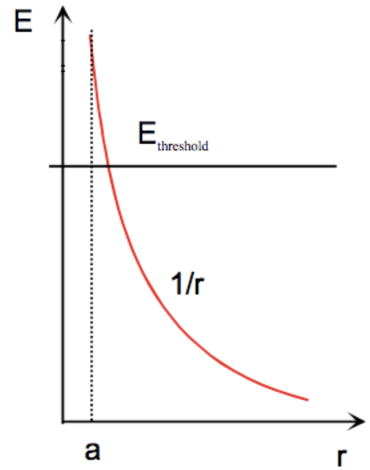
The simplest proportional counter: a wire

- Electrons drift towards anode wire. Field scale as $1/r$. Above a given value: cascade !
  - Typical gain: 10^4 - 10^5
  - Amplification time is typically ns
  - Measurement in one direction only



- Signal proportional to initial charge deposited: *dE/dx* measurement

$$E = \frac{C\,V_0}{2\,\pi\,\epsilon_0}\,\frac{1}{r}$$



- Typically a hundred e^-/ion pair
  - Not easy to detect: electronics noise ≈ 10 times higher

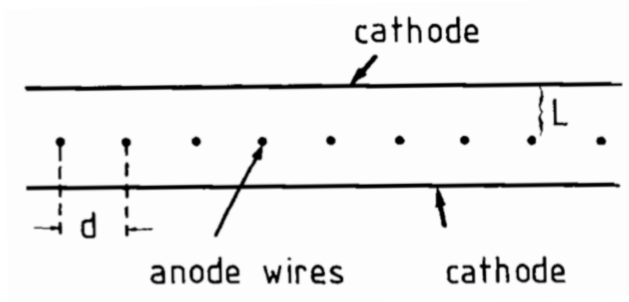
MWPC

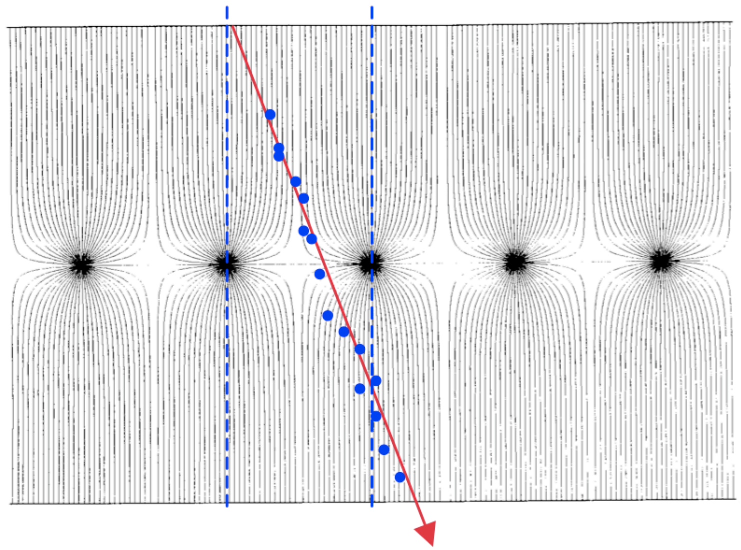
- Extension of this idea by Charpak et al (1968)
  - MWPC ≡ Multi Wire Proportional Chambers
  - Typically: L=5 mm, d=1 mm

- Resolution limited to

$$\sigma \approx \frac{d}{\sqrt{12}}$$

  - ie 300 μm for d = 1 mm



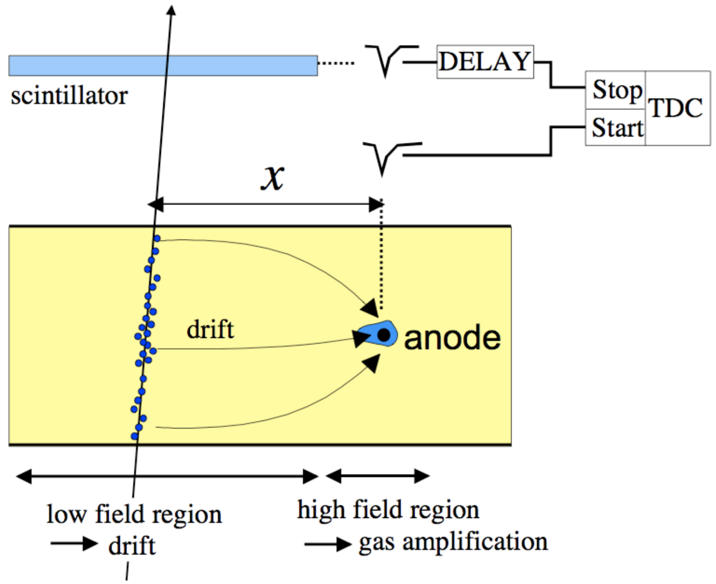


Field lines around the wires

Drift chambers

- Main drawback of MWPC: small detection volume
  - ➔ drift chambers
- Time measurement allow to measure *x* coordinate

$$x = \int v_D(t)\, dt$$



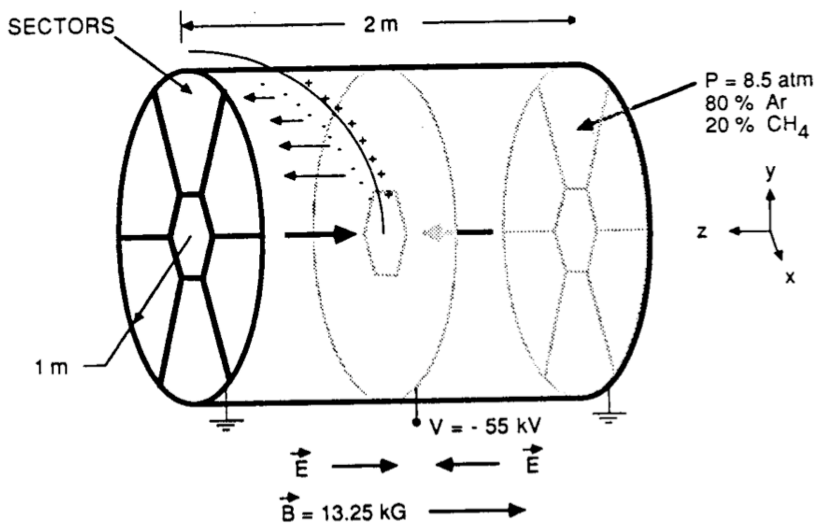
- Drawback: control of the electron drift in the gas
  - Diffusion
  - Calibration
  - Slow detection:
    - Typical drift time: 5 cm/μs (e^-), 500 μm/μs (ions)

An example: TPC's

1st TPC (PEP-4)

- TPC ≡ Time Projection Chamber
- *E*//*B* (solenoid)

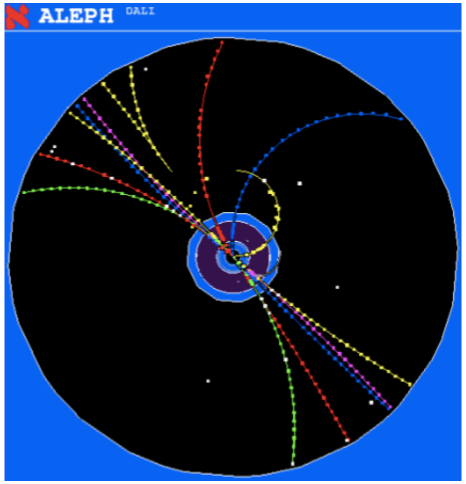
- Baseline of detectors for e^+e^- colliders
- Allow 3D reconstruction
  - *x* and *y* come from the wire and pad hited
  - *z* come from the time



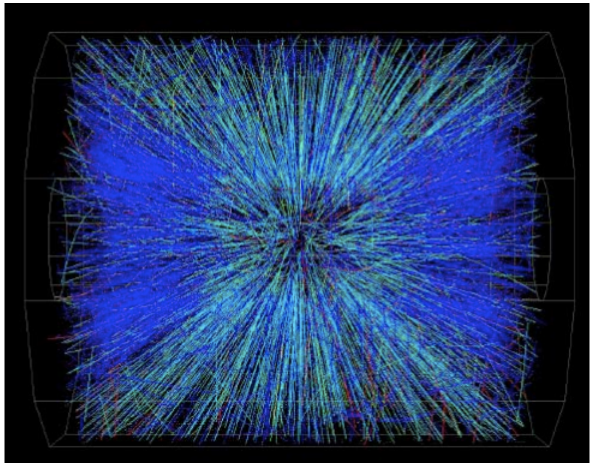
- Calibration required to know *E* in the complete volume

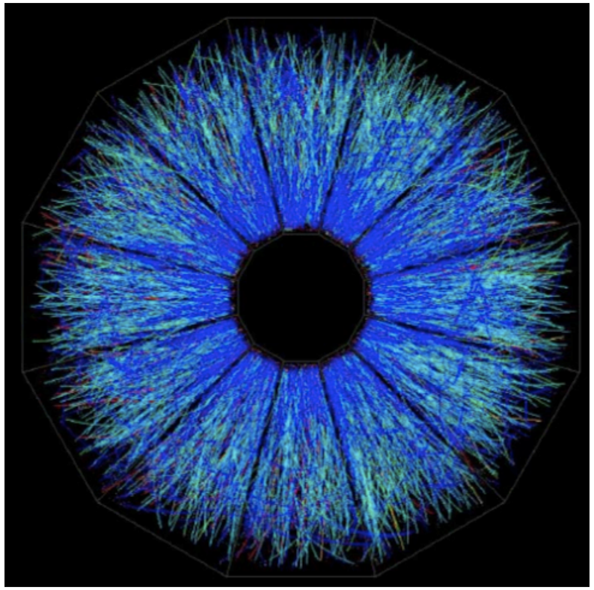
ALEPH and STAR TPC's

ALEPH : e^+e^-
(200 GeV)



STAR : Au+Au (130 GeV/nucleus)
with 2000 tracks

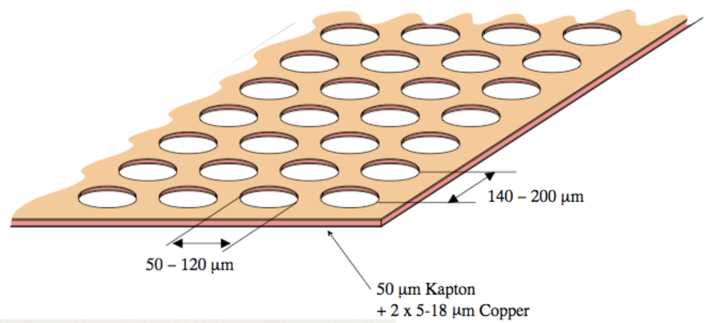


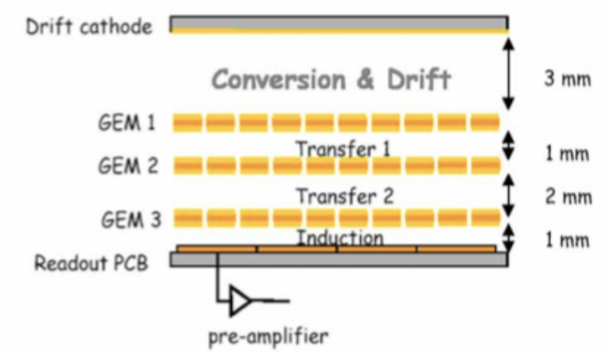


Recent development: GEM

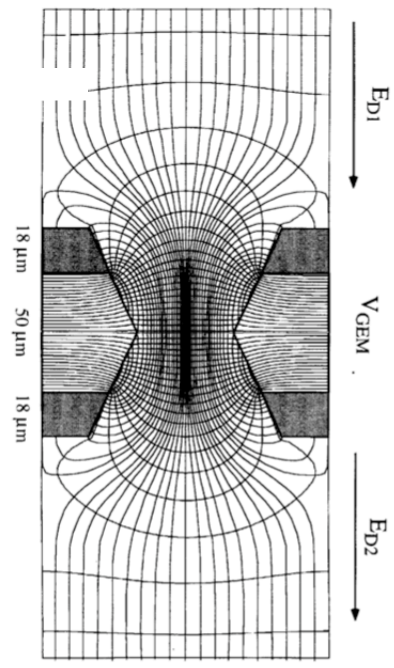
- GEM ≡ Gas Electron Multiplier
  - Foil Cu-Kapton-Cu with holes 30-50 μm
  - 200 to 400 V between both faces
  - 100 to 1000 e^- from a unique e^- entering a hole
  - Large detector possible
  - Possibility to put several detectors in a row

(R. Bouclier et al., NIM A 396 (1997) 50)





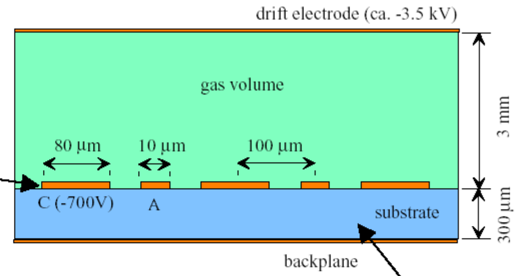
Muon detectors of LHCb



Recent development: MSGC

- MSGC ≡ Micro Strip Gas Chamber
- Small segmentation fine, small cellule (≈ 3-5 mm)
  - No longer fragile wires
  - Fast
  - Based on technologies coming from microelectronics
- Optimized for high fluxes

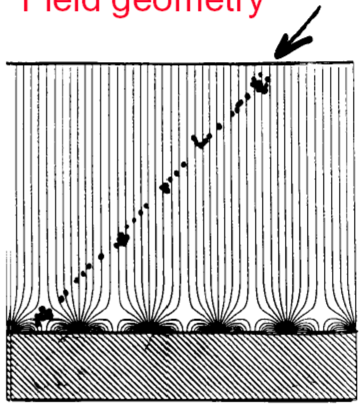
geometry and typical dimensions (former CMS standard)

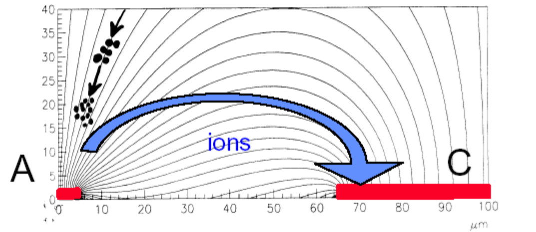


Gold strips + Cr underlayer

Glass DESAG AF45 + S8900 semiconducting glass coating, $\rho = 10^{16}\ \Omega/\square$

Field geometry





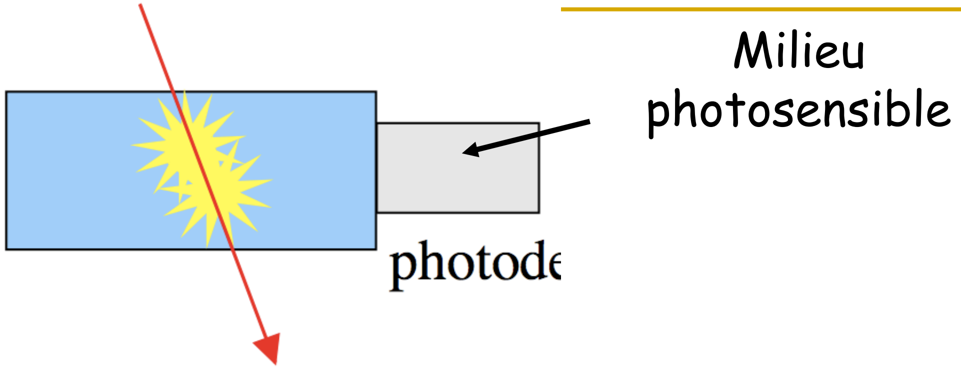
Fast ion evacuation → high rate capability ≈ 10^6 /($mm^2 \cdot s$)

Initially foreseen for CMS tracker

Plan

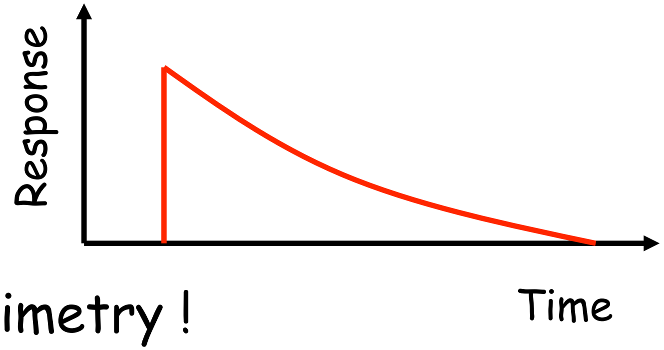
I. Interaction particle-matter

II. An example: charged tracks reconstruction
   1) Generalities
   2) Ionization detectors
   3) Scintillation detectors
   4) Semiconductors



- Two types of scintillators:
  - Inorganic scintillators
    - Dense, high yield, quite slow
    - Ideal for charged particles and γs
    - Expensive !
  - Organic scintillators
    - Light, low yield, quite fast
    - Low detection efficiency for γs
    - Low cost !

- Rising time is very fast (1-2 ns) and much faster than ioniation detectors
  - Used for trigger and time of flight systems
- Decrease of the signal is very slow (time constant ≈ 100-200 ns)



- Linear response (except low energy): calorimetry !
- Photons have to go through matter to arrive to the photon detection area. Number of transmitted photons is:

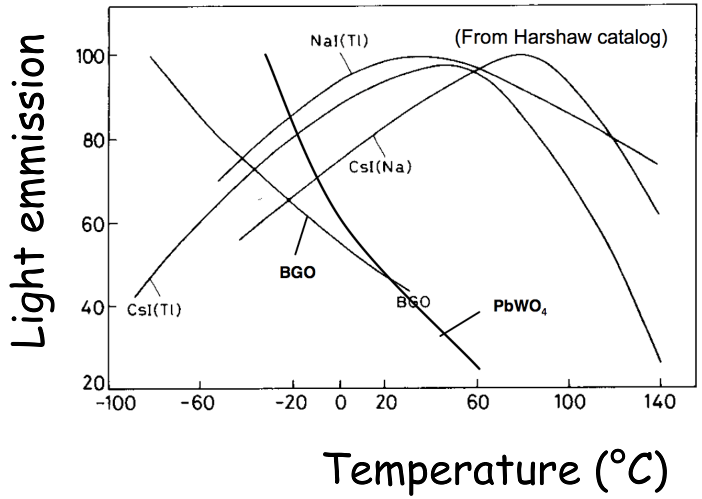
$$N(x) = N_0 \exp\left(-\frac{x}{\lambda}\right)$$

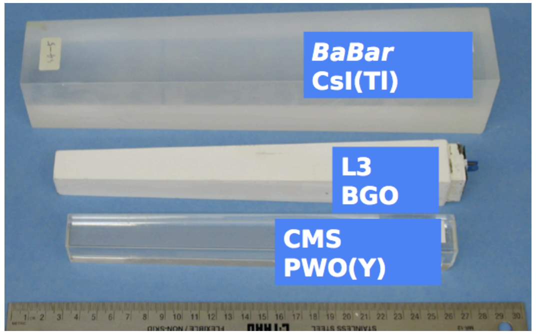
λ : attenuation length

- For large dimension detector, we need, $\lambda \approx 1$ m or higher

Inorganic scintillators

- Two types
  - Cristals (NaI, BaF_2, BGO, $PbWO_4$, ..)
    - Very often several time constants (from 1-2 ns to 100 ms) and not always the same wavelength (typically 200-500 nm)
    - Very high sensitivity to temperature
    - 10^3-10^4 photons/MeV, except for $PbWO_4$ ($\approx$ 100)





BaBar: CsI(TI) : 16 X_0

L3: BGO : 22 X_0

CMS: PWO(Y) : 25 X_0

« L » means « liquid »

- Noble liquids (LAr, LXe, LXr)
  - Several time constants (100 to 1000 ns), but same wavelength (120-170 nm)
  - 4 10^4 photons/MeV for LXe
  - drawback: cryogenics temperatures

- In both cases, fluorescence is due to intermediate states form impurities in matter

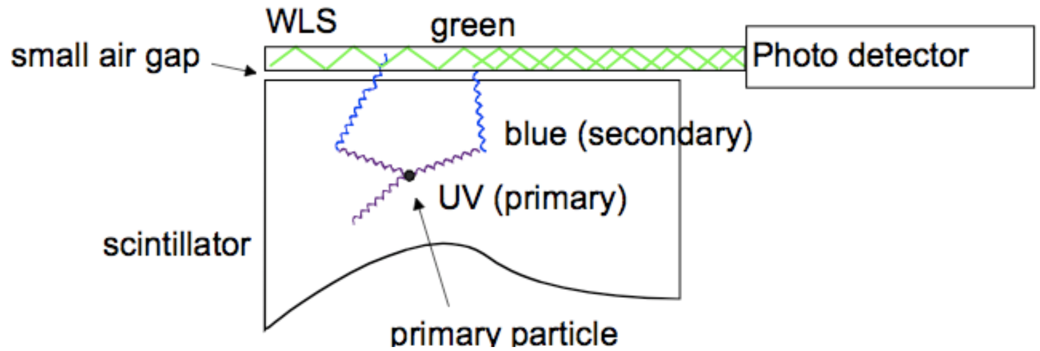
Organic scintillators

- Usually called scintillators (liquid or plastic)
  - Mix (delicate) of a main component with impurities whose role is to shift the radiation towards higher wavelengths: Wave Length Shifting (WLS)
  - Those impurities absorb scintillation photons and emit photons very quickly (≈ 1 ns) with a wavelength easier to detect (typically from 300 to 500 nm)

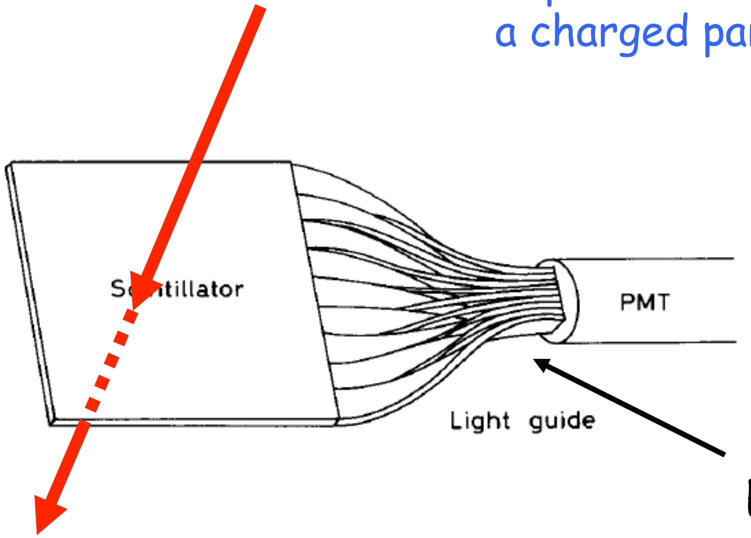
Some examples

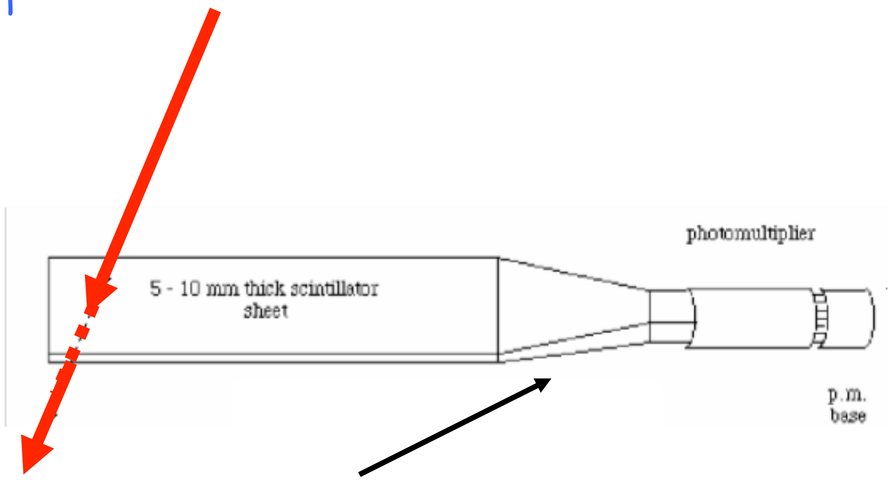
	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene	p-terphenyl DPO PBD	POPOP TBP BBO DPS

- About 10^4 photons/MeV
- schematics:



Examples how to detect
a charged particle



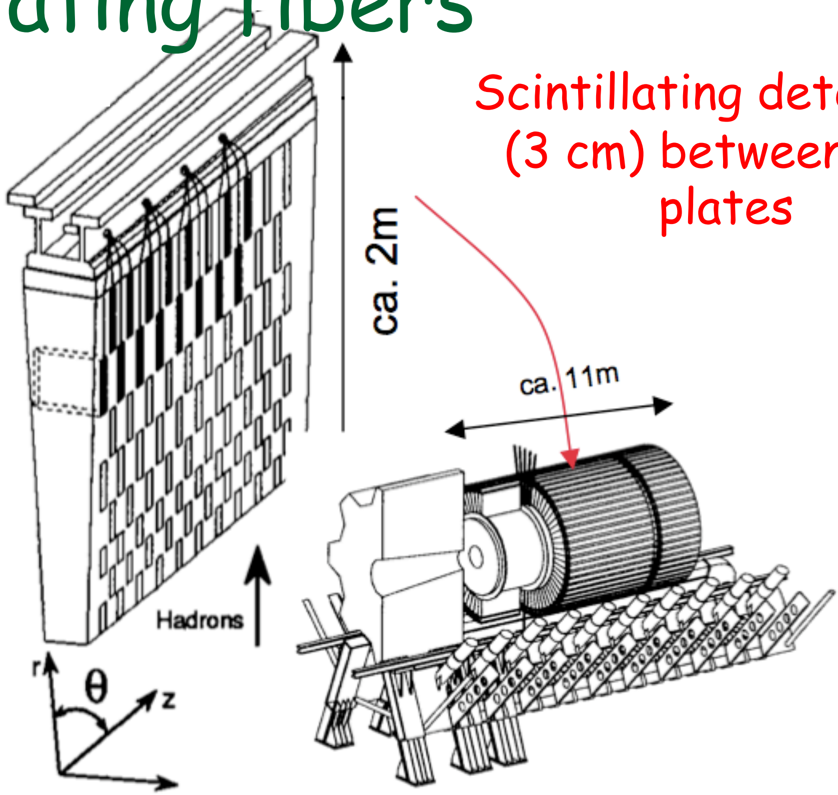


Efficiency ≈ 20-30%

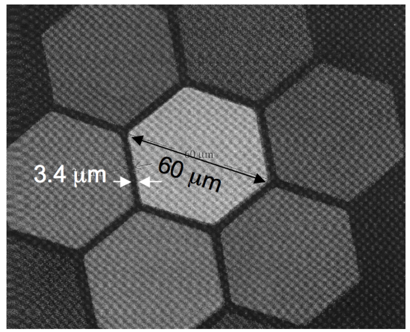
Application: scintillating fibers

- Calorimetry:

ATLAS hadronic calorimeter



- Tracking:
  - Round, square or hexagonal fibers, …



Plan

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- Semiconductors are a special type of ionization detectors: instead of exciting (or ionizing), a charged particle crated quasi free e-/holes pairs
  - Charged are collected by an electric field

- One uses:
  - silicon: charged particles and photons
  - germanium: photons

- ≈ 3 eV are needed to create a pair e-/home (for Si and Ge), ≈ 30 eV for a ionization detector and ≈ 300 eV for a scintillator !!

Conclusions

- Particle interaction with matter treated with Bethe-Block formalism is enough in most cases
- This is the root for all sensitive devices