



European School of Instrumentation  
in Particle & Astroparticle Physics



European Scientific Institute

# DETECTOR TECHNOLOGIES

## Lecture 1: Principles of detection

- Generalities about detectors
- Interaction of particles with matter

## **Goal :**

Observation and identification of final states  
(whatever the processus)

## **A particle :** Mass

Electrical Charge

Moment

Energy

Lifetime

~~(spin, flavour, color....)~~

## **A Detector :** does not give any measurement.

Gives an information coming after an **interaction**  
with the particle

## Energy deposition

- **Limited** (the particle goes almost undisturbed)

Momentum

Electrical charge (if magnet)

→ Trajectography

- **Total** (the particle stops)

Energy

## Various processes

But first : some important notions  
(supposed to be known ?)

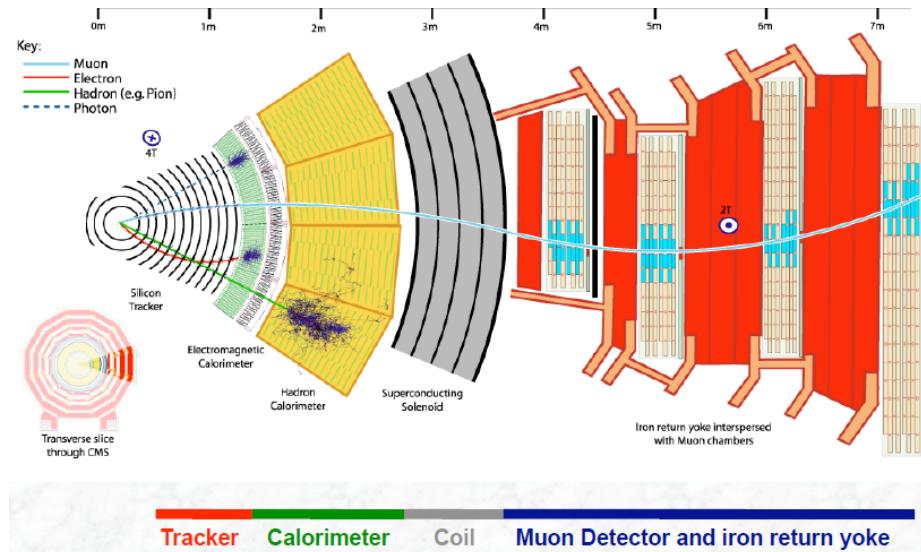
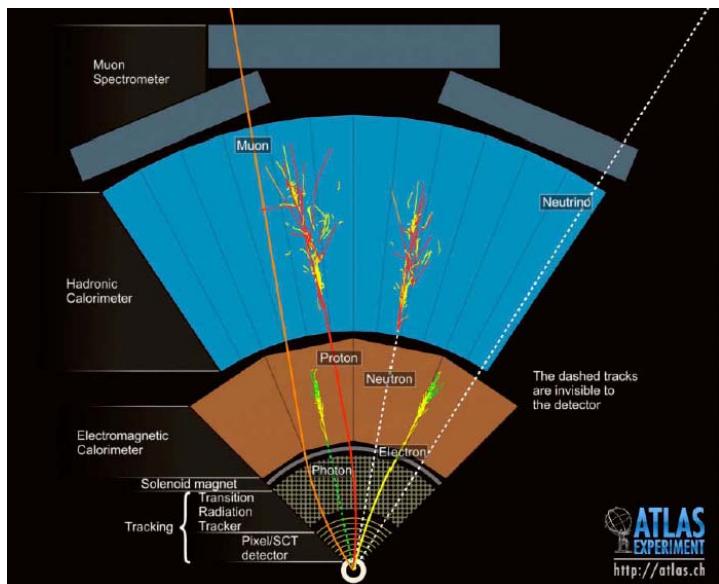
## Types of detectors :

Trackers (position and momentum measurement)

Calorimeters (energy measurement)

Identifiers (identification of various types of particles)

Trigger counters (decision)



## CROSS SECTION :

Probability of a phenomenon (interaction with the detector) to occur.

$$\frac{d\sigma}{d\Omega}(E, \Omega) = \frac{1}{F} \frac{dN_s}{d\Omega}$$

$$\sigma(E) = \int d\Omega \frac{d\sigma}{d\Omega}$$

F = incident flux of particles  
Ns = emitted number of particles  
 $\Omega$  = Solid angle

## MEAN FREE PATH :

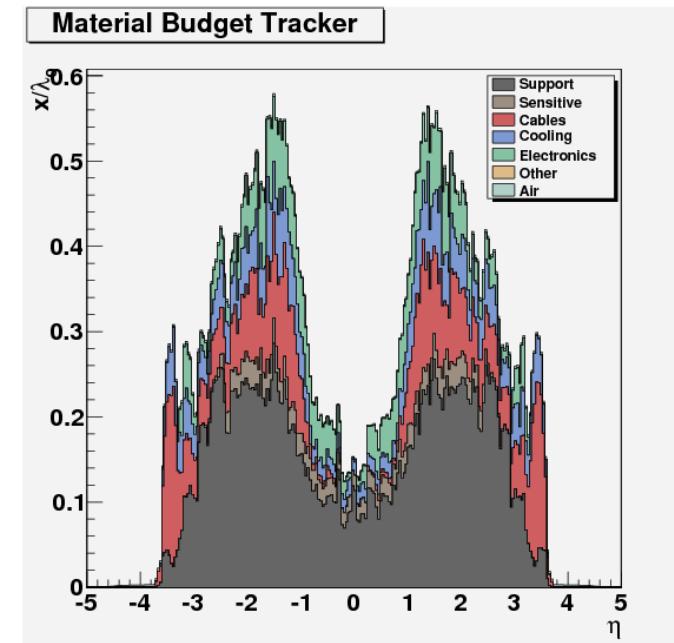
Average distance travelled by a particle between 2 consecutive interactions in matter (detector) :

$$\lambda = \frac{1}{\sigma \cdot n}$$

$\sigma$  = total interaction cross section

n = number of interactive centers per unit volume

Example :  
The CMS tracker  
material budget in unit  
of interaction length



## TIME OF FLIGHT :

For particles with a timelife of  $\tau_0$  :

$$N(t) = N_0 e^{-\frac{t}{\tau_0}}$$

Of course, in the laboratory, for a particle with a speed  $v$ ,

$$\tau = \gamma \tau_0 \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

and then,

## DISTANCE OF FLIGHT :

Mean distance in the detector for a particle with a lifetime  $\tau_0$   
measured in the laboratory (without interactions....)

$$L = v t = \beta c \tau = \beta \gamma c \tau_0 = \frac{p c \tau_0}{m}$$

High energetic particle (particles at speed  $\approx c$ )  
**quasi-transparent detector**

<b>Particle</b>	<b><math>c \tau</math> (cm)</b>
$\gamma$	$\infty$ (stable)
$e^+ / e^-$	$\infty$ (stable)
$\mu$	$6.6 \cdot 10^4$
neutrino	$\infty$ (stable)
$\pi^0$	$2.5 \cdot 10^{-6}$
$\pi^+ / \pi^-$	780
$K^+ / K^-$	371
$K_s^0$	2.7
$K_l^0$	1554
p	$\infty$ (stable)
n	$2.7 \cdot 10^{13}$
H	$10^{-12}$

## INTERACTION OF PARTICLE WITH MATTER :

Depends on the type of interactions

**ELECTROMAGNETIC** :  $\lambda \approx \mu\text{m}$

ionization

pairs creation ( $e^+ e^-$ , electrons – holes...)

photon emission (Bremstrahlung, Cerenkov effect)

**STRONG** :  $\lambda \approx \text{cm}$

hadronic showers of neutrons

(but the observed signal will be due to EM interaction)

**WEAK** :  $\lambda \approx 10^{15} \text{ m}$  (neutrinos)

**GRAVITY** : ??

Depends on the type of particle

**CHARGED**

**NEUTRAL**

And of course, **ENERGY, MEAN FREE PATH, LIFETIME**

# **DETECTOR and PARTICLES and INTERACTIONS ...**

In order to detect a particle, it must

- interact with the material of the detector
- transfer some energy in a recognizable way (signal to be processed)

## **4 CLASSES OF PARTICLES**

Heavy ( $m > m_e$ ) charged particles

Light ( $m \approx m_e$ ) charged particles

Photons

Hadrons

## **3 POSSIBILITIES**

Ionization (EM)

Radiation (EM)

Nuclear Interaction (Strong)

## 1. HEAVY ( $m > m_e$ ) CHARGED PARTICLES : IONIZATION

Energy loss (energy transferred to the medium ) by ionization in MeV g<sup>-1</sup> cm<sup>2</sup>

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Bethe-Bloch, 1932

Where :  $K = 4 \pi N_A r_e^2 m_e = 0.3071$  (**relative to the electron**)

$A, Z$  : atomic mass and number **relative to the medium**

$N_A$  : Avogadro's number

$T_{\max}$  : maximum possible energy transferred to an electron in the medium  
 $\sim 2m_e \beta^2 \gamma^2$  (see J. Collot's lecture)

$z$  : charge of the incoming particle

$\beta, \gamma$  : relatives to the particle

→ dE/dX in MeV.g<sup>-1</sup>.cm<sup>2</sup>  
→ valid only for  $M > m\mu$

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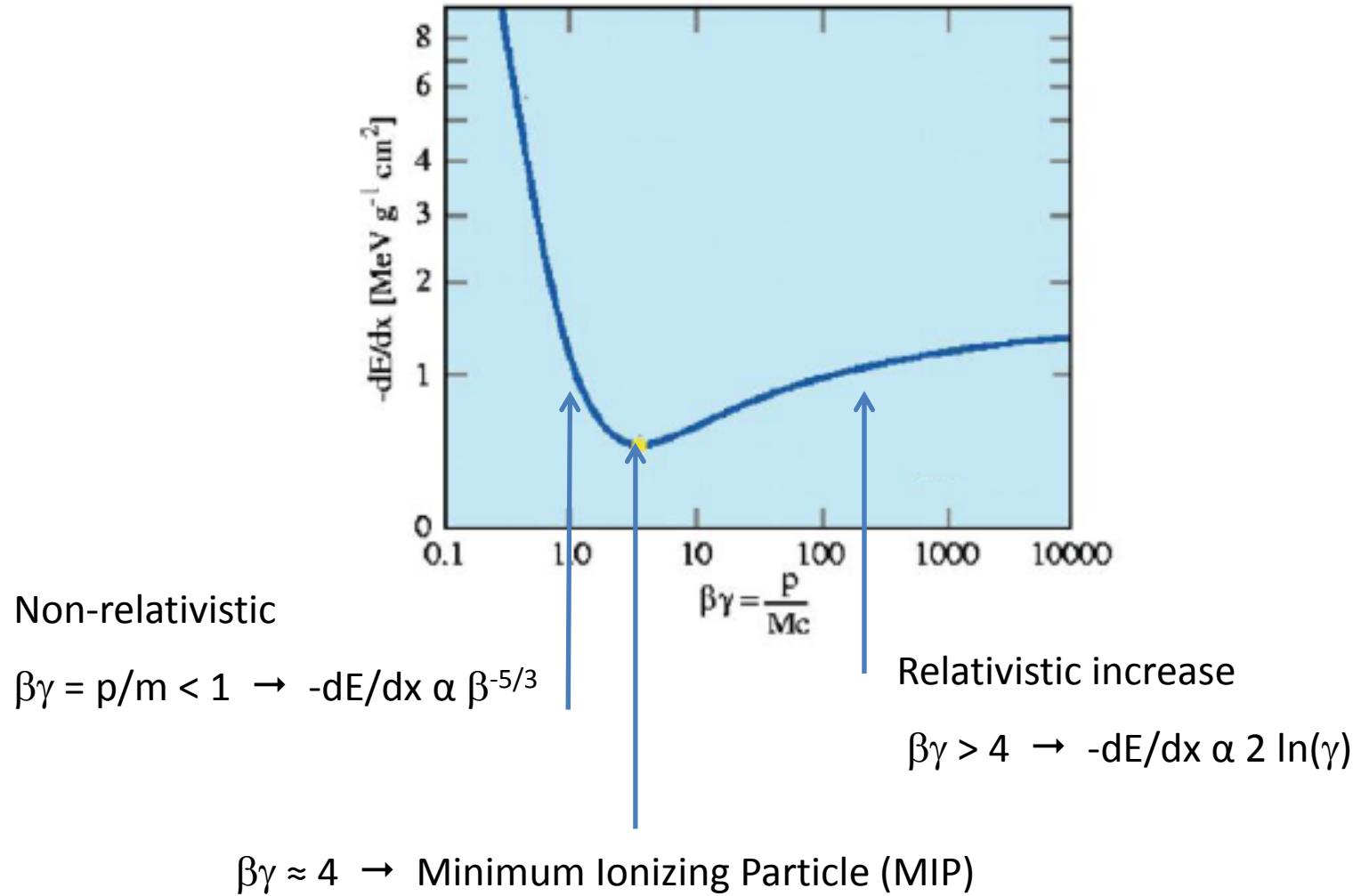
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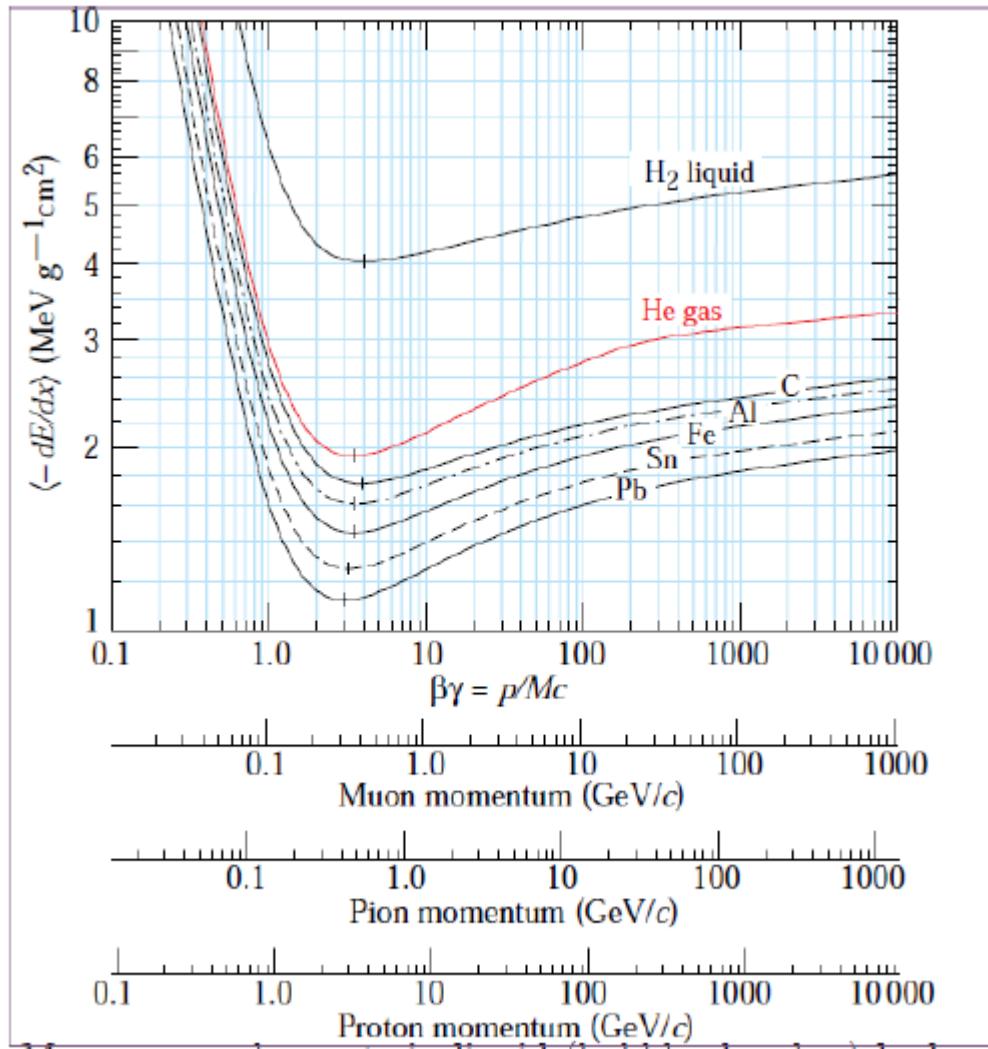
$\beta, \gamma$  : relatives to the particle

- $dE/dX$  in MeV.g<sup>-1</sup>.cm<sup>2</sup>
- valid only for  $M > m_\mu$
- **$dE/dX$  depends on  $\beta$ ,**
- **$dE/dX$  does not depend on  $M$**

## HEAVY ( $m > m_e$ ) CHARGED PARTICLES : IONIZATION



## HEAVY ( $m > m_e$ ) CHARGED PARTICLES : IONIZATION

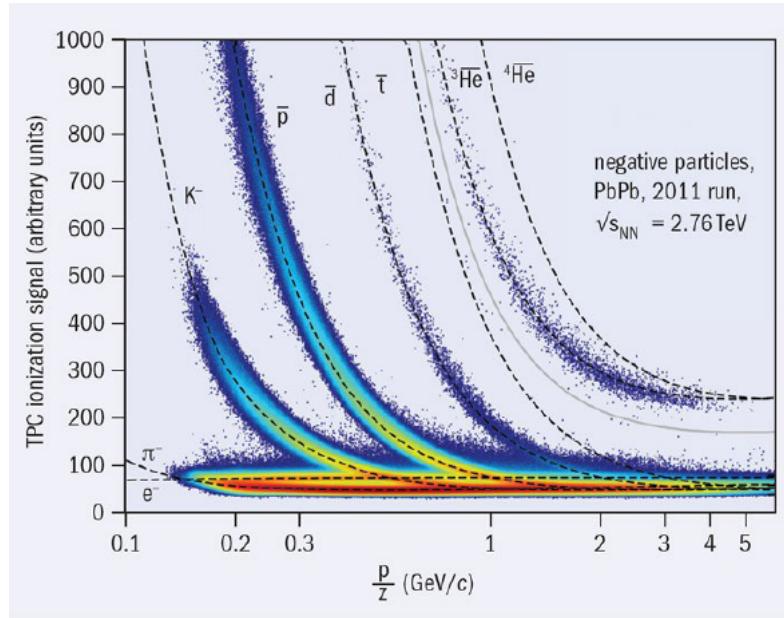


Relativistic rise :

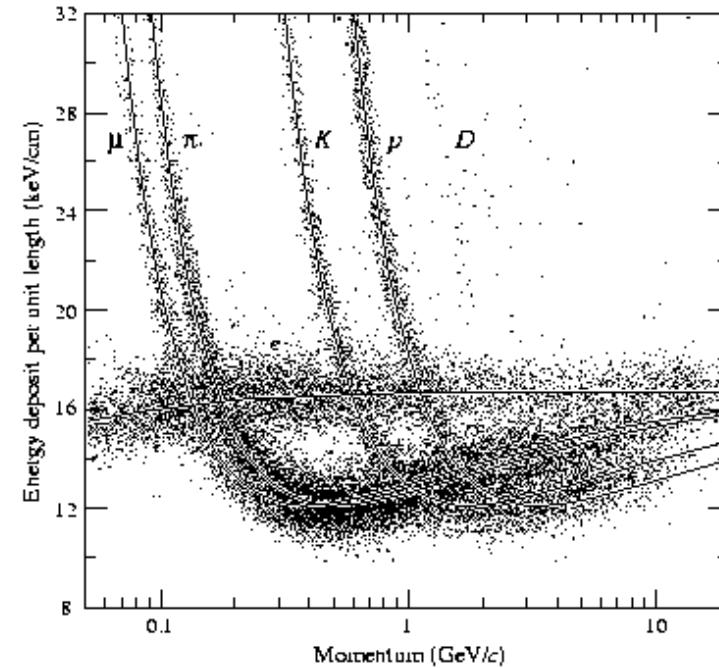
- more distant collisions, increasing the transverse electric field with  $\gamma$
- Typical for

$$\begin{aligned} \text{gas : } & 1.5 \\ \text{liquid : } & 1.1 \end{aligned}$$

## HEAVY ( $m > m_e$ ) CHARGED PARTICLES : IONIZATION



Direct identification by energy loss  
in Ne-CO<sub>2</sub> 90-10 %  
(ALICE TPC)



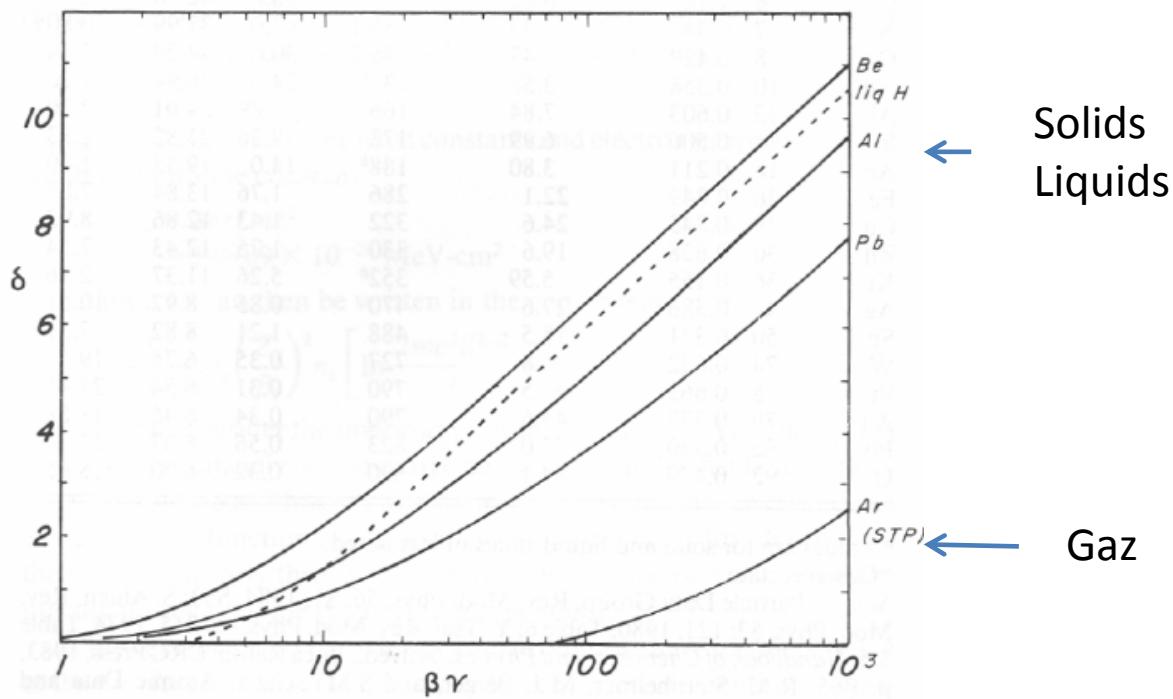
Direct identification by energy loss  
in Ar-CH<sub>4</sub> 80-20 %  
(DELPHI)

## HEAVY ( $m > m_e$ ) CHARGED PARTICLES : IONIZATION

Corrections to the Bethe-Bloch formula :

**Density effect** : the density of the medium will have a screening effect on the relativistic rise (important for solids and liquids)

Figure 2.5 Density effect correction parameter  $\delta$  for several materials.  
(The parameter was calculated using the formulas and coefficients given in R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables 30: 261, 1984.)



## 2. LIGHT ( $m \approx m_e$ ) CHARGED PARTICLES : IONIZATION

Corresponds to an energy loss by charged particle : Bethe-Bloch

**But :** small mass : electrons may be deflected

interaction electron – electron : collisions between identical particles

$$\text{Bethe-Bloch : } -\left(\frac{dE}{dx}\right) = \left(\frac{4\pi N_A \alpha^2 (\hbar c)^2}{m_e}\right) z^2 \frac{\rho Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2(\beta\gamma)^2 m_e \epsilon_{\max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right]$$



$$\text{Bethe-Bloch For electrons } \left(\frac{dE}{dx}\right)_{ION} = \left(\frac{2\pi N_A \alpha^2 (\hbar c)^2}{m_e}\right) \frac{\rho Z}{A} \frac{1}{\beta^2} \left[ \ln \frac{(\beta\gamma)^2 m_e T}{2I^2} - \ln 2 \left( \frac{2}{\gamma} - \frac{1}{\gamma^2} \right) + \frac{1}{\gamma^2} \right]$$

### 3. CHARGED PARTICLES : RADIATION (Bremsstrahlung)

For any charged particle :

When accelerated (or decelerated), in the nucleus electrical field, any charged particle emits photons

#### § 6. Energy Loss of Fast Electrons by Radiation.

For very high energies (case 2) the integration gives

$$-\left(\frac{dE_0}{dx}\right)_{\text{rad}} = N \frac{Z^2 r_0^2}{137} E_0 \left(4 \log 183 Z^{-\frac{1}{3}} + \frac{2}{9}\right) \quad (\text{for } E_0 \gg 137 mc^2 Z^{-\frac{1}{3}}),$$

From : Bethe, H.A., Heitler, W., 1934. On the stopping of fast particles and on the creation of positive electrons

$$-\frac{dE}{dx}^{\text{rad}} \left( \frac{\text{MeV}}{\text{g/cm}^2} \right) = \frac{0.3071}{A(g)} \frac{\alpha}{\pi} Z^2 z^2 \left( \frac{m_e}{m} \right)^2 \frac{E}{m_e} \ln \left( \frac{183}{Z^{1/3}} \right)$$

Z : médium  
z, m, E : particle

$$\begin{aligned} \left( \frac{m_e}{m} \right)^2 &= 1 \text{ for } e^+, e^- \\ &= 1.3 \cdot 10^{-5} \text{ for } \mu \\ &= 2.3 \cdot 10^{-5} \text{ for } \pi \\ &= 2.7 \cdot 10^{-7} \text{ for } p \end{aligned}$$

Up to 100 GeV, one can neglect the Bremsstrahlung if particle  $\neq e^+$  or  $e^-$

## CHARGED PARTICLES : RADIATION (Bremsstrahlung)

For electrons,

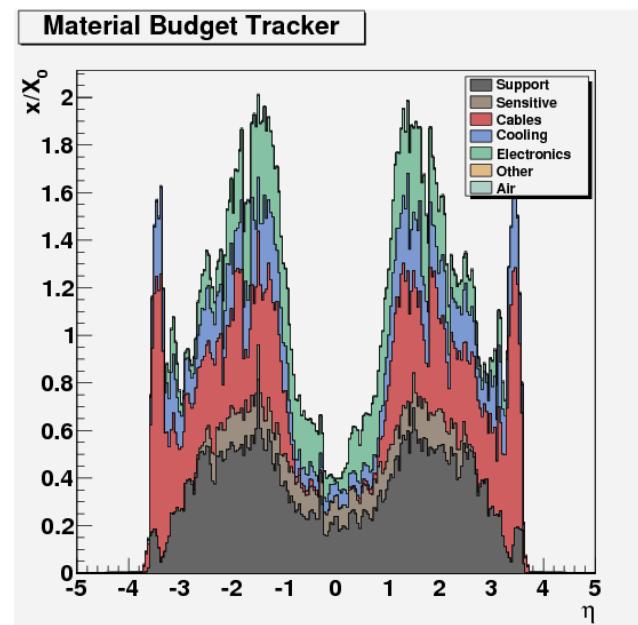
$$-\frac{dE}{dx}^{rad} \left( \frac{MeV}{g/cm^2} \right) = \frac{0.3071}{A(g)} \frac{\alpha}{\pi} Z^2 z^2 \left( \frac{m_e}{m} \right)^2 \frac{E}{m_e} \ln \left( \frac{183}{Z^{1/3}} \right)$$

Can be rewritten as

$$-\frac{dE}{dx}^{rad} (e^-) = \frac{E}{X_0} \quad X_0 (g/cm^2) = \frac{716.4 A(g)}{Z(Z+1) \ln \left( \frac{287}{Z^{1/2}} \right)}$$

**X<sub>0</sub>** : radiation length (characteristic of the medium)

Example :  
The CMS tracker  
material budget in unit  
of rad. length



Medium	X <sub>0</sub> (g.cm <sup>-2</sup> )
Hydrogen	63.1
Helium	94.3
Carbon	42.7
Aluminium	24.0
Iron	13.8

## CONSEQUENCE : CRITICAL ENERGY

The energy loss has 2 components :

- ionization (for heavy and energetic particles, it is  $\approx$  constant)
- radiation ( for heavy particles, it is almost negligible) proportional to E

$$\frac{dE}{dx} = \left( \frac{dE}{dx} \right)_{\text{ion}} + \left( \frac{dE}{dx} \right)_{\text{rad}}$$

The critical energy ( $E_c$ ) is defined as the energy at which the two mechanisms are equal

$$E_c = \frac{610 \text{ MeV}}{Z+1.24}$$

For liquids and solids

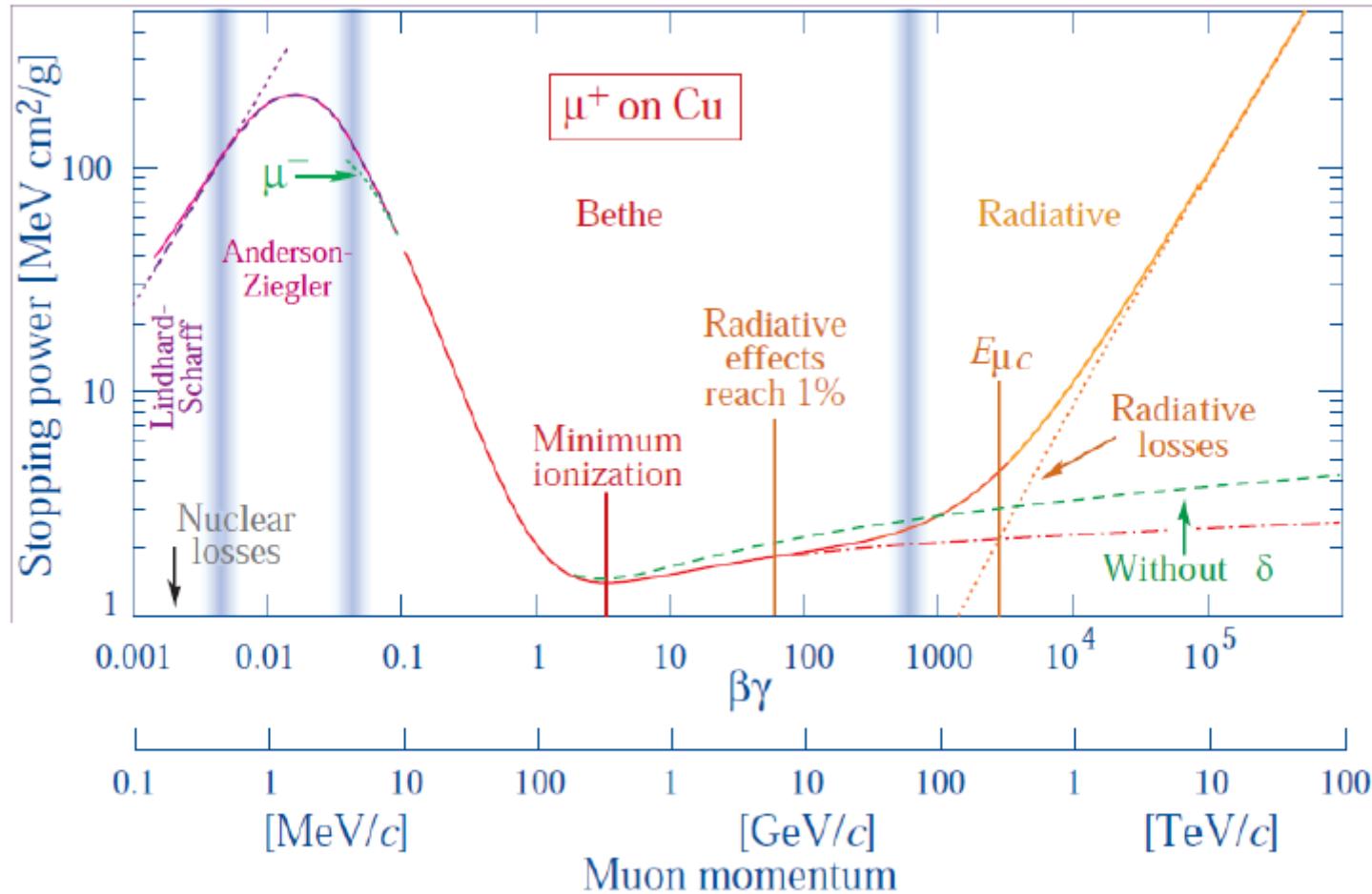
$$E_c = \frac{710 \text{ MeV}}{Z+0.92}$$

For gas

<i>medium</i>	<i>Z</i>	<i>A</i>	<i>X<sub>0</sub> (g/cm<sup>2</sup>)</i>	<i>X<sub>0</sub> (cm)</i>	<i>E<sub>C</sub> (MeV)</i>
hydrogen	1	1.01	63	700000	350
helium	2	4	94	530000	250
lithium	3	6.94	83	156	180
carbon	6	12.01	43	18.8	90
nitrogen	7	14.01	38	30500	85
oxygen	8	16	34	24000	75
aluminium	13	26.98	24	8.9	40
silicon	14	28.09	22	9.4	39
iron	26	55.85	13.9	1.76	20.7
copper	29	63.55	12.9	1.43	18.8
silver	47	109.9	9.3	0.89	11.9
tungsten	74	183.9	6.8	0.35	8
lead	82	207.2	6.4	0.56	7.4
air	7.3	14.4	37	30000	84
silica ( SiO <sub>2</sub> )	11.2	21.7	27	12	57
water	7.5	14.2	36	36	83

Note : table for electrons only (the most sensitive)  
for other particles, it would scale to the square of the particle mass

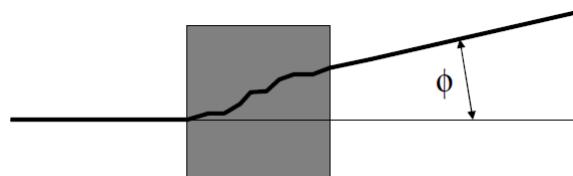
## INTERACTION OF CHARGED PARTICLES



## 4. CHARGED PARTICLES (Hadrons) : Coulomb scattering and interactions

Hadrons are interacting mainly with the nucleus by (strong interaction)

- collisions (coulomb))
- interaction (strong force)



$$\phi_{\text{rms}} = \langle \phi^2 \rangle^{1/2} = \frac{z E_s}{p v} \sqrt{\frac{t}{X_0}}$$

X

Phenomenon governed by the interaction lengths  $\lambda_T$  (collisions) and  $\lambda_i$  (interactions)

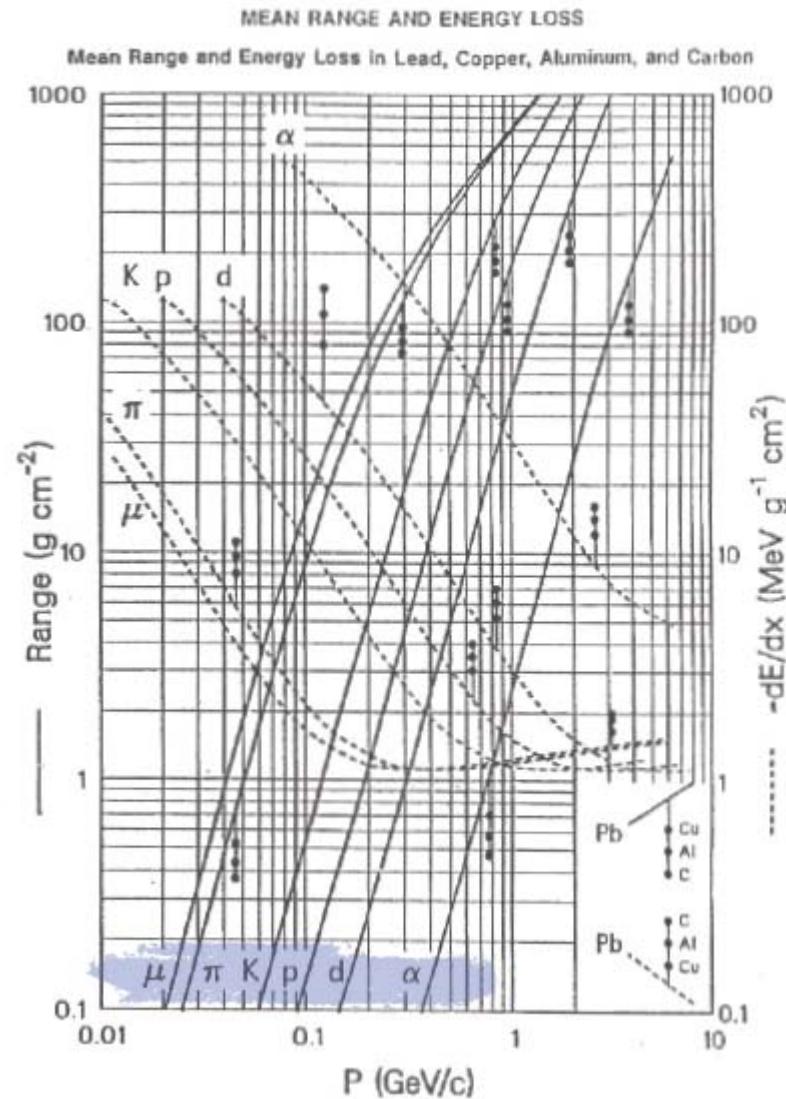
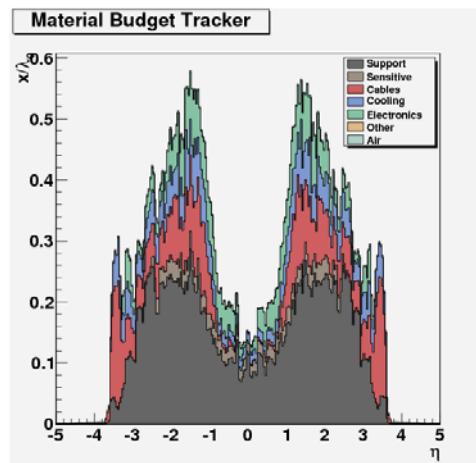
$$\lambda_T = \frac{A}{N_A \sigma_T} \text{ g cm}^{-2}$$

$$\lambda_i = \frac{A}{N_A \sigma_{inelastic}} \text{ g cm}^{-2}$$

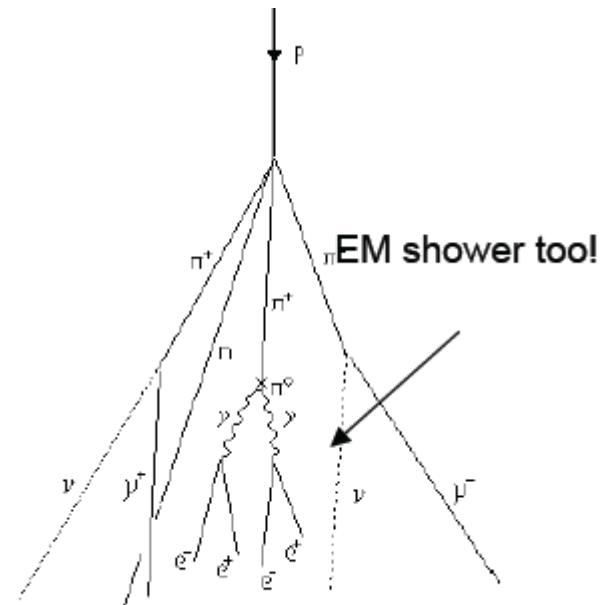
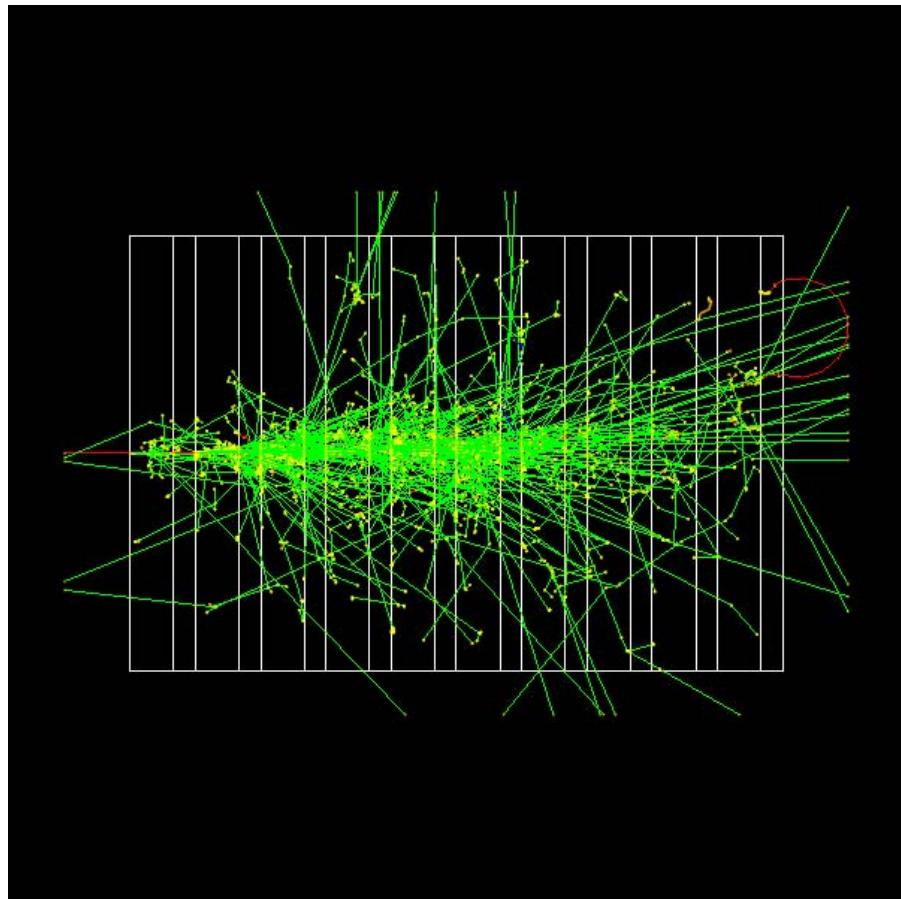
Range : measured of the stopping power  
for various material  
for different energies (momentum)

$$R(T_0) = \int_0^{T_0} \frac{dT}{dE}(T)$$

Example :  
The CMS tracker  
material budget in unit  
of interaction length



Hadronic shower :  $\lambda$  instead of  $X_0$

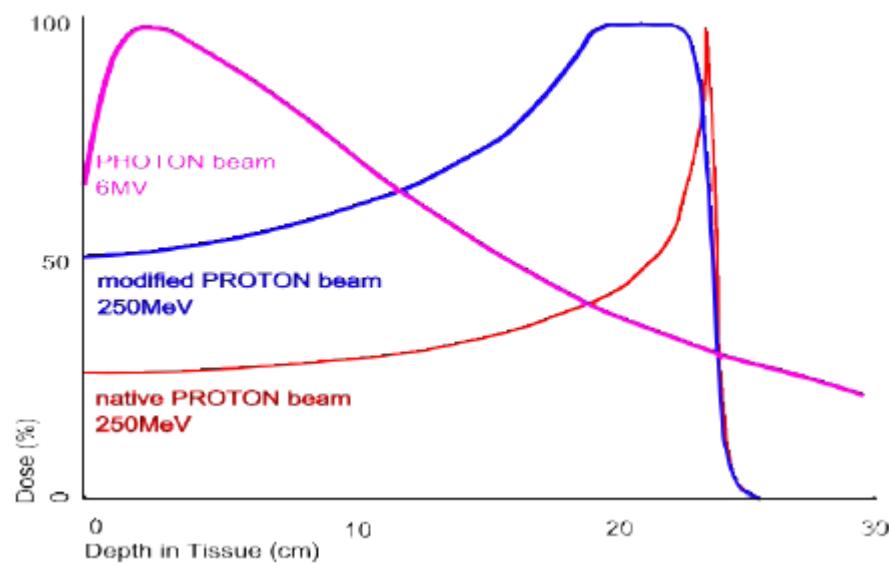
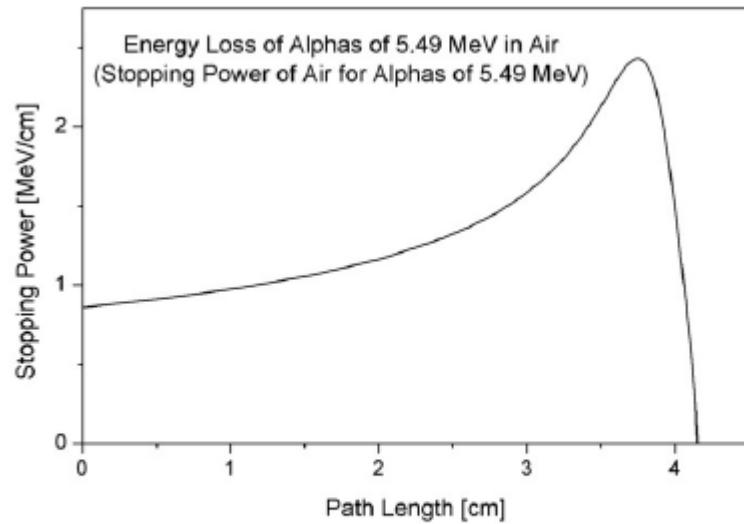


## CONSEQUENCE : RANGE IN MATTER

In a medium a particle will loose its energy **by any means**  
(ionization radiation, scattering) until it **stops** in the medium

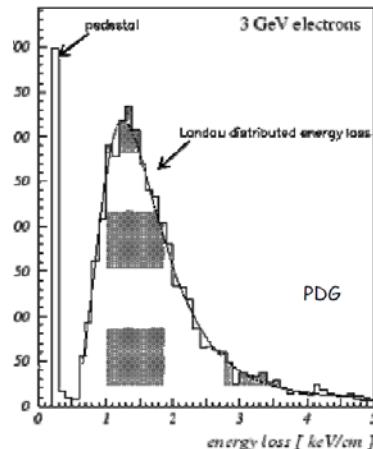
Of course, it depends on the MASS and ENERGY of the incoming particle  
Of course, it depends on the DENSITY and the THICKNESS of the medium

Almost negligible for High Energy Physics



## ENERGY LOSS DISTRIBUTION

The Bethe-Bloch formula describes the **average** energy loss of charged particles.  
 But there can be large fluctuations which have an effect on larger energy losses  
 The fluctuation around the mean is described by an assymetric distribution



Landau distribution :

$$\Omega(\lambda) = \frac{1}{\sqrt{2\pi}} \exp \left\{ -\frac{1}{2}(\lambda + e^{-\lambda}) \right\}$$

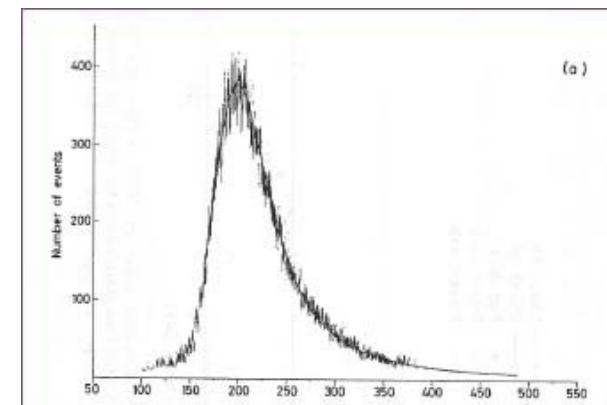
$$\lambda = \frac{\Delta E - \Delta E_{MP}}{\varepsilon}$$

$$\epsilon = 0.3071 \times \frac{z^2 Z}{2 \cdot A(g) \beta^2} \text{ MeV}$$

$$\Delta E_{MP} = \Delta E_{Bethe} + \epsilon \left( \beta^2 + \ln \left( \frac{\epsilon}{T_{max}} \right) + 0.194 \right) \text{ MeV}$$

In fact, for thin absorbers, the reality is more a convolution  
 of a Landau and a Gaussian distribution...

Energy deposited by 736 MeV/c proton in Silicon  
 $(X_0 = 9.4 \text{ cm}, E_c = 39 \text{ MeV for electrons})$



## 5. INTERACTION OF PHOTONS

Photons are interacting with matter through 3 types of processes:

- Photoelectric emission → Absorption

$$\sigma \sim 1 / E^3$$

- Compton scattering → Deflection

$$\sigma \sim 1 / E$$

- Pair production → Absorption

$$\sigma \sim \text{constant (above threshold)}$$

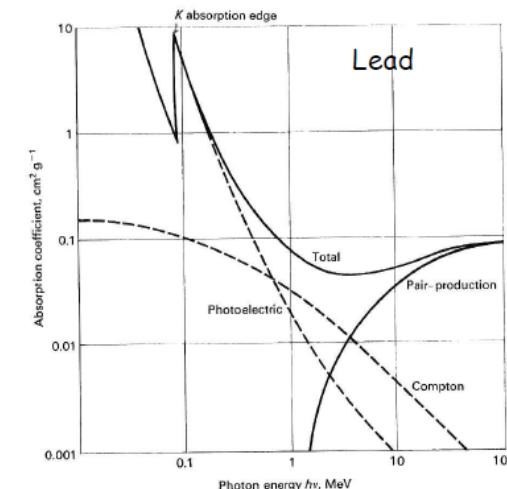
Note : Main effect : electron production.

Attenuation

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

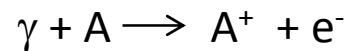
$\mu$  : relative to the medium and the absorption cross section

$$\sigma_{\text{ABS}} = \sigma_{\text{phot}} + \sigma_{\text{Compton}} + \sigma_{\text{pairs}}$$



## INTERACTION OF PHOTONS : PHOTOELECTRIC EMISSION

A. Einstein, 1905



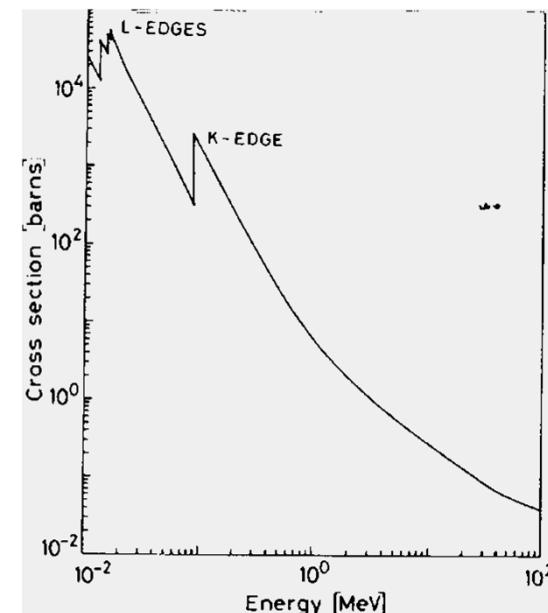
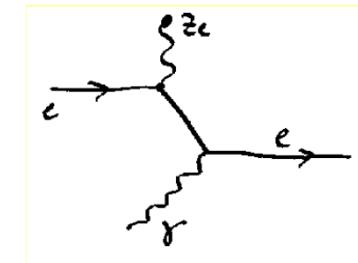
Again : Energy transfert to an electron :

$$E_e = E_\gamma - E_{\text{binding}}$$

For  $E_\gamma > E_{\text{binding}}$        $\sigma_{\text{phot}} \sim Z^5 / E_\gamma^{7/2}$

For  $E_\gamma \gg E_{\text{binding}}$        $\sigma_{\text{phot}} \sim Z^5 / E_\gamma$

Dominant process for  $E_\gamma < 100 \text{ keV}$

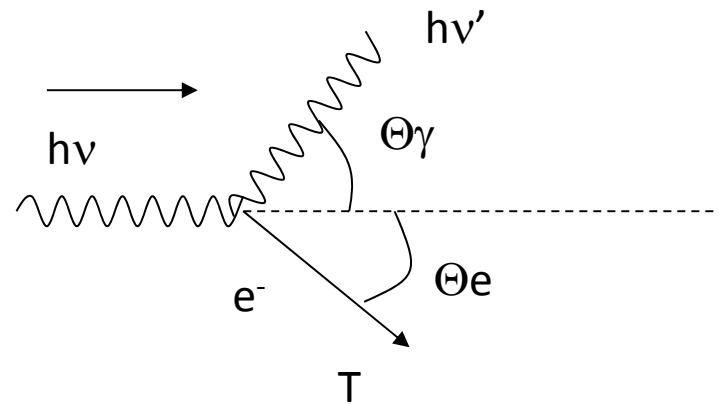


## INTERACTION OF PHOTONS : COMPTON SCATTERING

$$\frac{E_{\gamma}'}{E_{\gamma}} = \frac{1}{1+\epsilon(1-\cos\theta_{\gamma})} \quad \text{with } \epsilon = \frac{E_{\gamma}}{m_e}$$

$$\cotg \theta_e = (1+\epsilon) \tg \left( \frac{\theta_{\gamma}}{2} \right)$$

$\Theta_e$  can not be  $> \pi/2$



Cross section : calculated using QED :  
Klein – Nishima formula

$$\frac{d\sigma_c^e}{d\Omega} = \frac{r_e^2}{2} \frac{1+\cos^2\theta_{\gamma}}{(1+\epsilon(1-\cos\theta_{\gamma}))^2} \left( 1 + \frac{\epsilon^2(1-\cos\theta_{\gamma})^2}{(1+\cos^2\theta_{\gamma})(1+\epsilon(1-\cos\theta_{\gamma}))} \right) \quad (\text{per electron})$$

Integrating over  $\Omega$  :

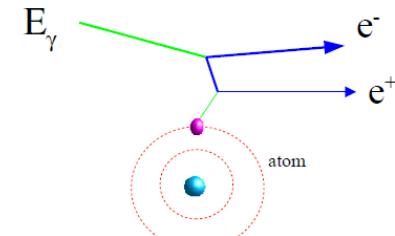
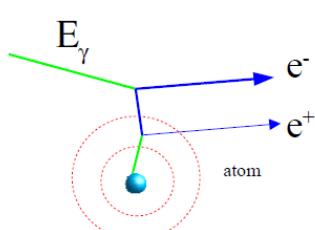
$$\sigma_{\text{Compton}} = 2\pi r_e^2 \left( \frac{1+\epsilon}{\epsilon^2} \right) \left\{ \frac{2(1+\epsilon)}{1+2\epsilon} - \frac{1}{\epsilon} \ln(1+2\epsilon) \right\} + \frac{1}{2\epsilon} \ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2} \quad (\text{per electron})$$

$\sigma_{\text{Compton}} \propto Z/E_{\gamma}$

## INTERACTION OF PHOTONS : PAIRS PRODUCTION



Needs a nucleus  
or another electron...



Threshold :

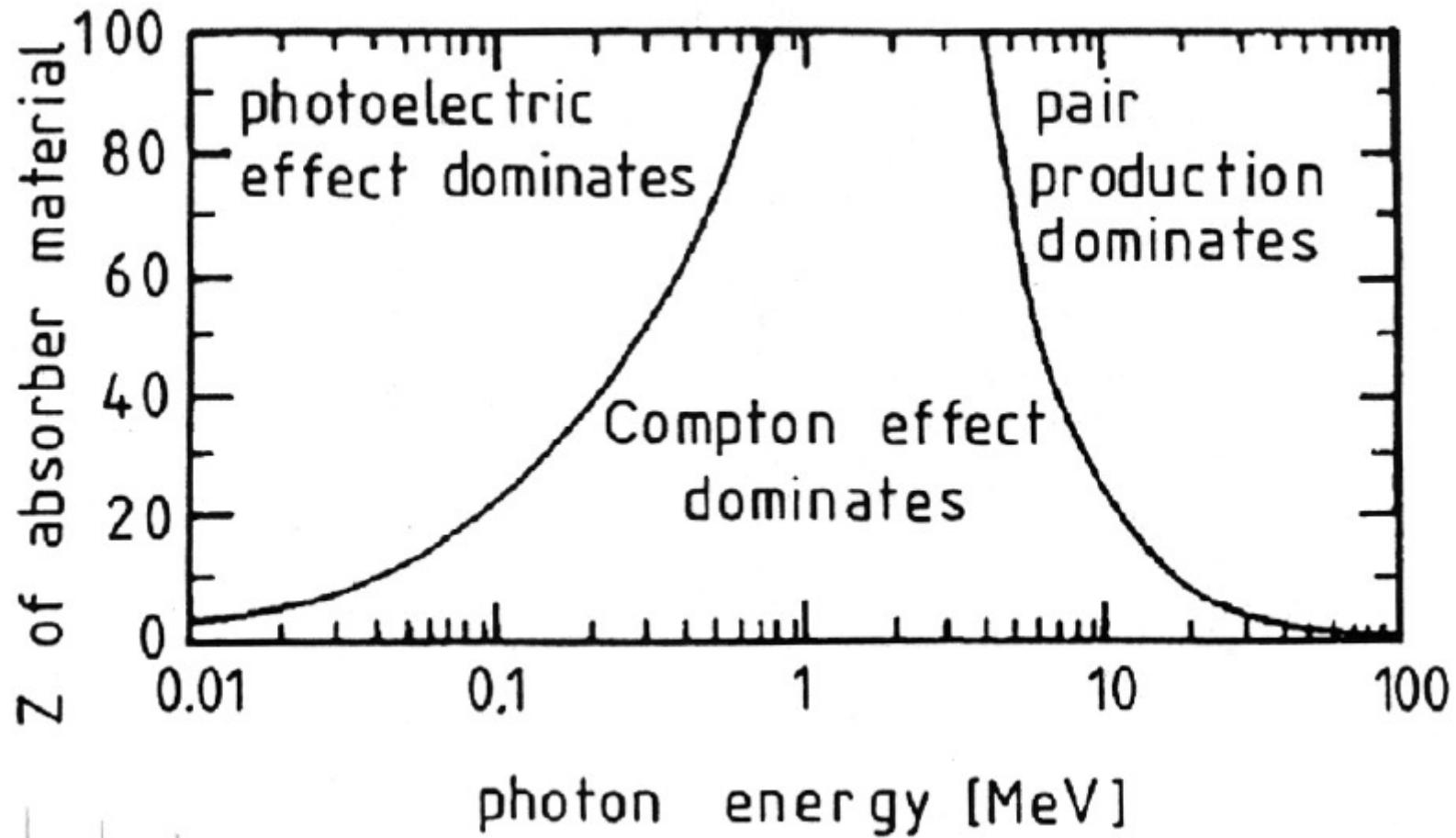
$$E_\gamma \geq 2m_e + 2 \frac{m_e^2}{m_{nucleus}}$$

And because  $m_{nucleus} \gg m_e$   $E_\gamma \geq 2m_e \approx 1,022\text{MeV}$

Cross section :  $\sigma_{pair} = Z^2 \ln\left(\frac{E_\gamma}{m_e c^2}\right)$

For higher energies ( $> 10 \text{ MeV}$ ) :  $\sigma_{pair} = \frac{7}{9} 4\alpha r_e Z^2 \ln \frac{183}{Z^{1/3}}$

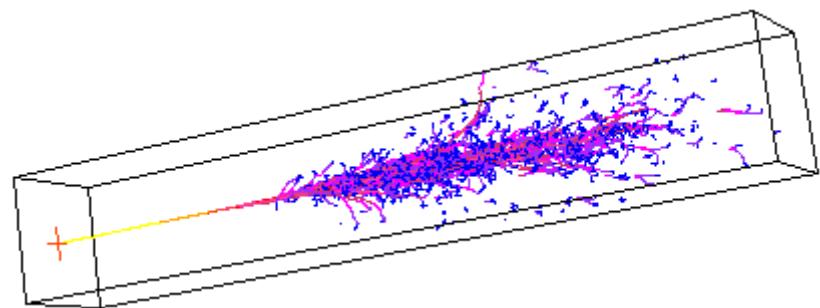
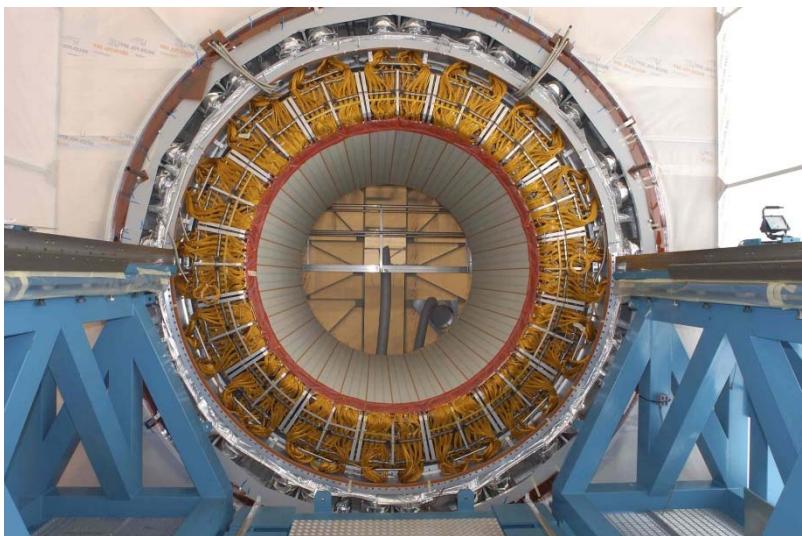
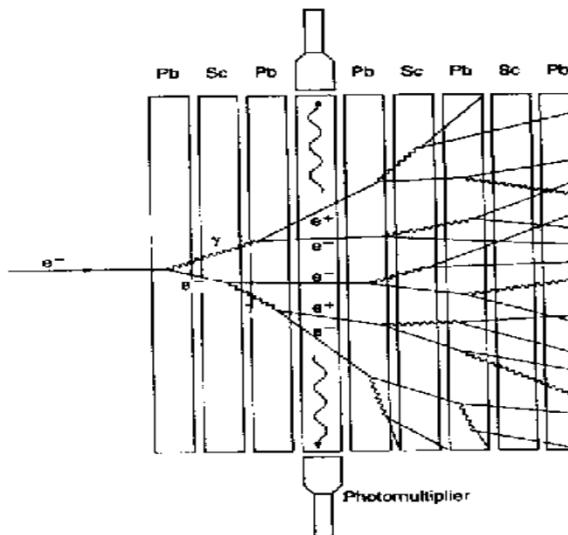
Note : If enough energy, the positron will annihilate with another electron, producing another photon, which will annihilate in a pair ...  
 → Electromagnetic shower



## INTERACTION OF PHOTONS : shower

Note : brems

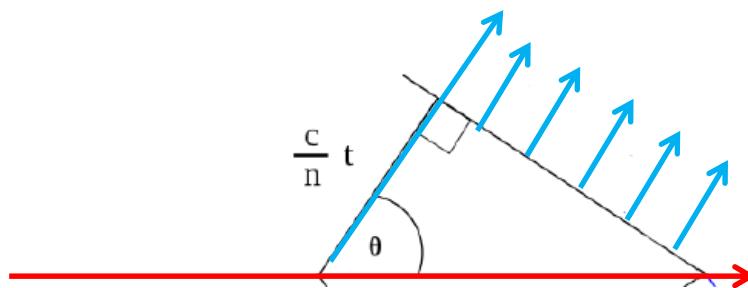
Electromagnetic shower



The ATLAS electromagnetic calorimeter

## 6. CERENKOV EMISSION

When a particle is moving faster than the velocity of light in a given medium  
 → production of photons



$$\cos \theta = \frac{c/nt}{\beta ct} = \frac{1}{\beta n}$$

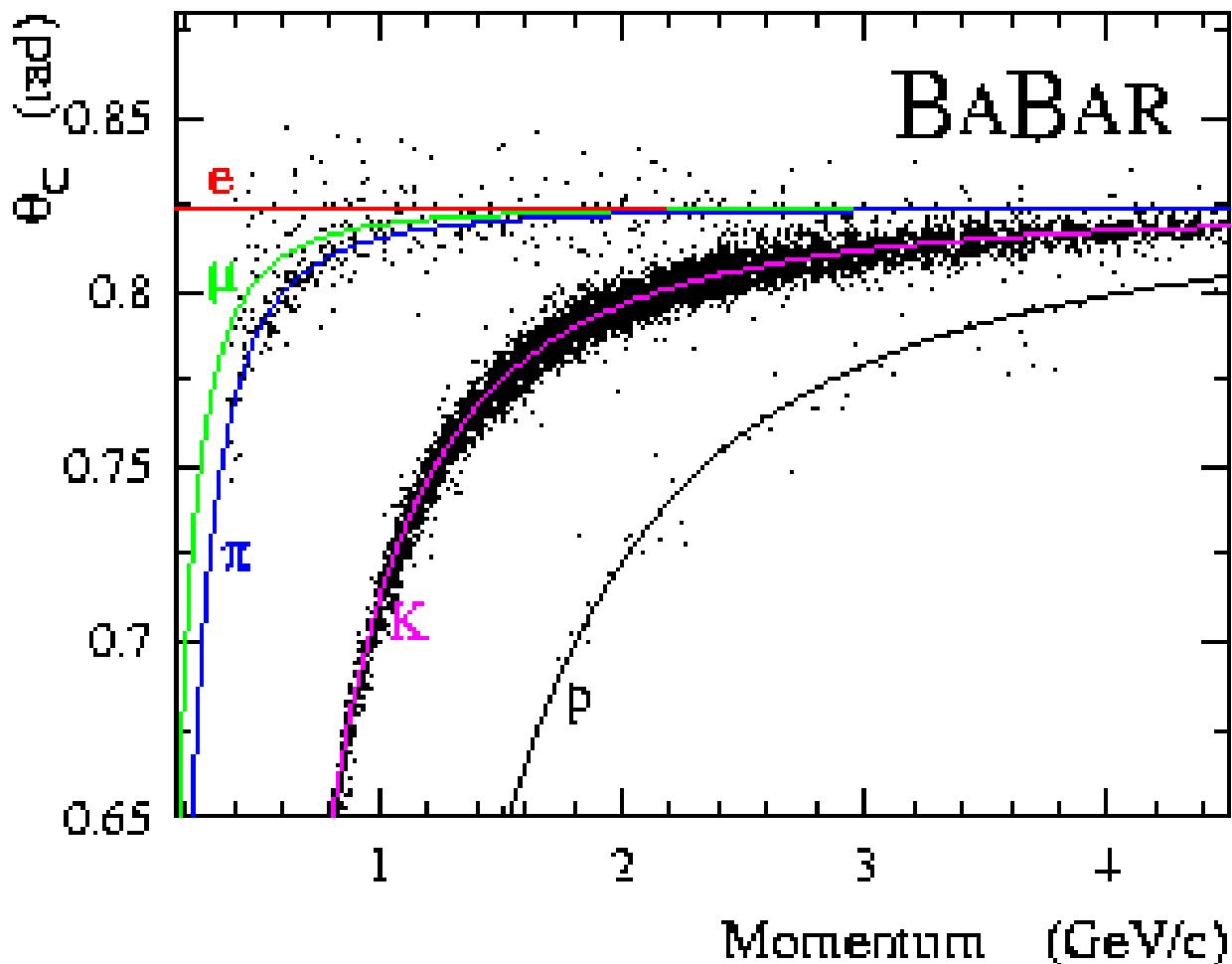
Threshold :  $\beta > \frac{1}{n}$  (n is the refractive index of the medium)

Photon production is rather small :  $\frac{dN}{dx d\lambda} = 2\pi a \frac{1}{\lambda^2} \left(1 - \frac{1}{\beta^2 n^2}\right)$

Energy loss is very small (can be neglected):  
 $10^{-3} \text{ MeV.cm}^2.\text{g}^{-1}$  for solids  
 $0.01 - 0.2 \text{ MeV.cm}^2.\text{g}^{-1}$  for He, H2



Typical :  $0.35 \mu\text{m} < \lambda_{\text{cerenkov}} < 0.55 \mu\text{m}$



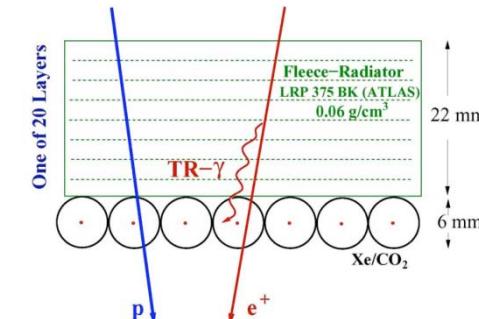
Identification of particles by measurement of  $\Theta$  (Experience Babar)

## 7. TRANSITION RADIATION

**Transition radiation** is a photon emission (X) occurring when a charged particle passes through inhomogeneous media, such as a boundary between two different media with different dielectric properties

Emission at an angle       $\cos \theta = \frac{1}{\gamma}$

Very low rate  $\sim 1/2 \alpha$  (fine structure constant)



In the momentum range 1 – 10 GeV, only electrons produce transition radiation with a relatively low probability (1%) per boundary crossing.

Thus, a TRD is mostly used for electron identification.

