Introduction to interaction of radiation with matter

Matteo Franchini

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University of Bologna

Charged Particles

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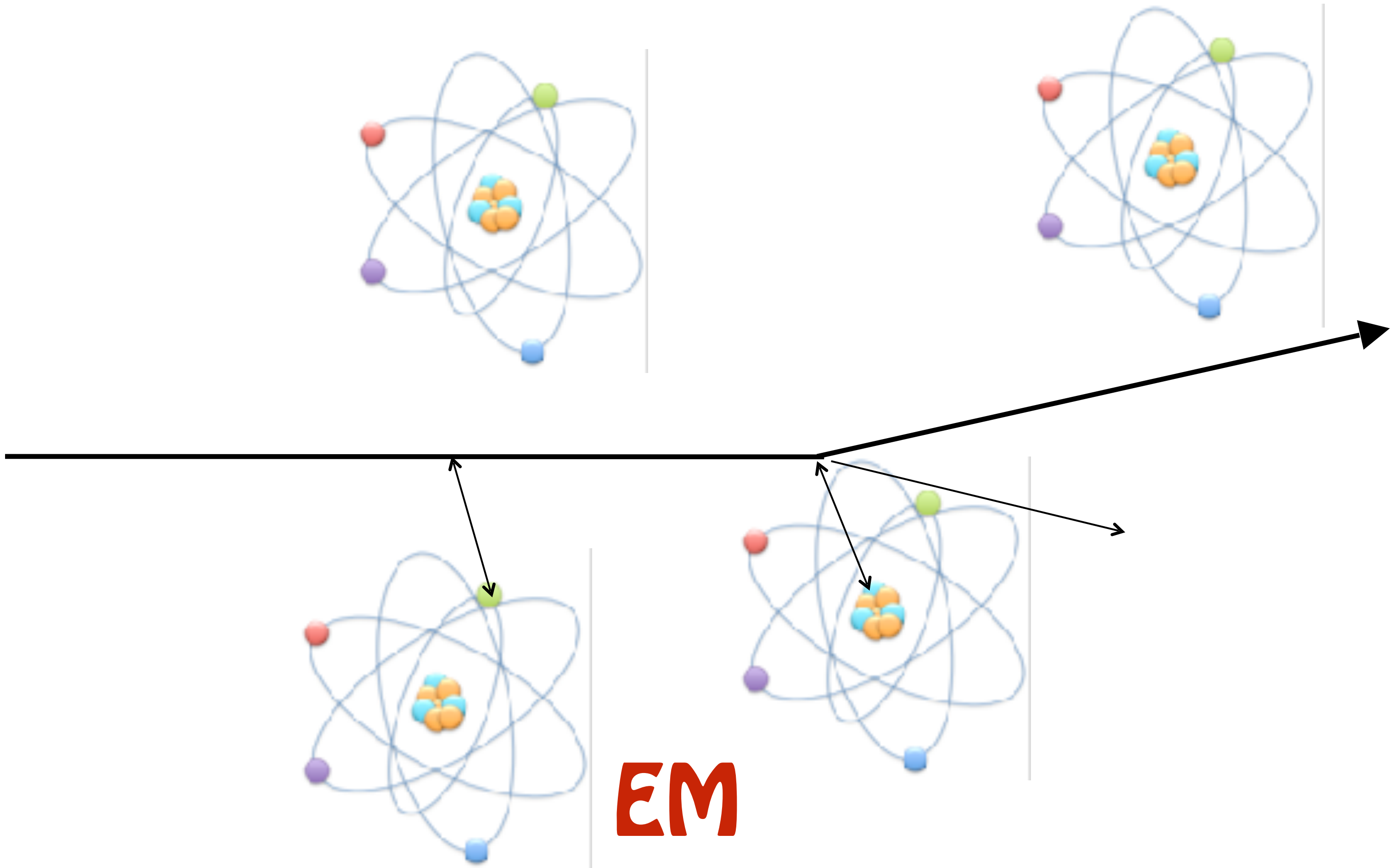


Charged particles way of interacting is divided in:

- Electrons
- Heavy Charged Particles ($m > m_{electron}$)

Interaction with atomic electrons. Particle loses energy; atoms are **excited** or **ionized**.

Interaction with atomic nucleus. Particle undergoes **multiple scattering**. Could emit a **bremsstrahlung** photon.

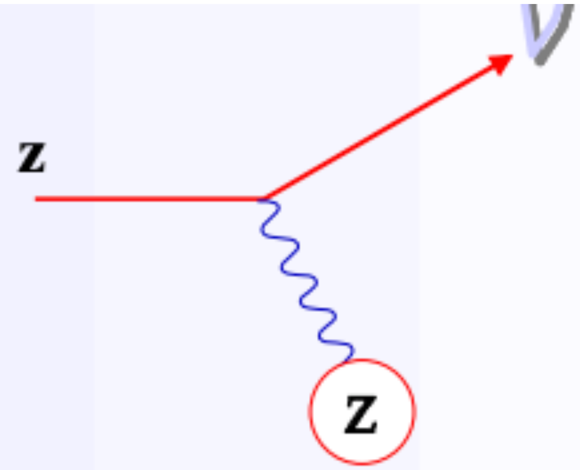
Others:

- Cherenkov
- Strong interaction (nuclear fragmentation, …)

Cross-section

Scattering

An incoming particle with charge z interacts elastically with a target of nuclear charge Z.
The cross-section for this e.m. process is

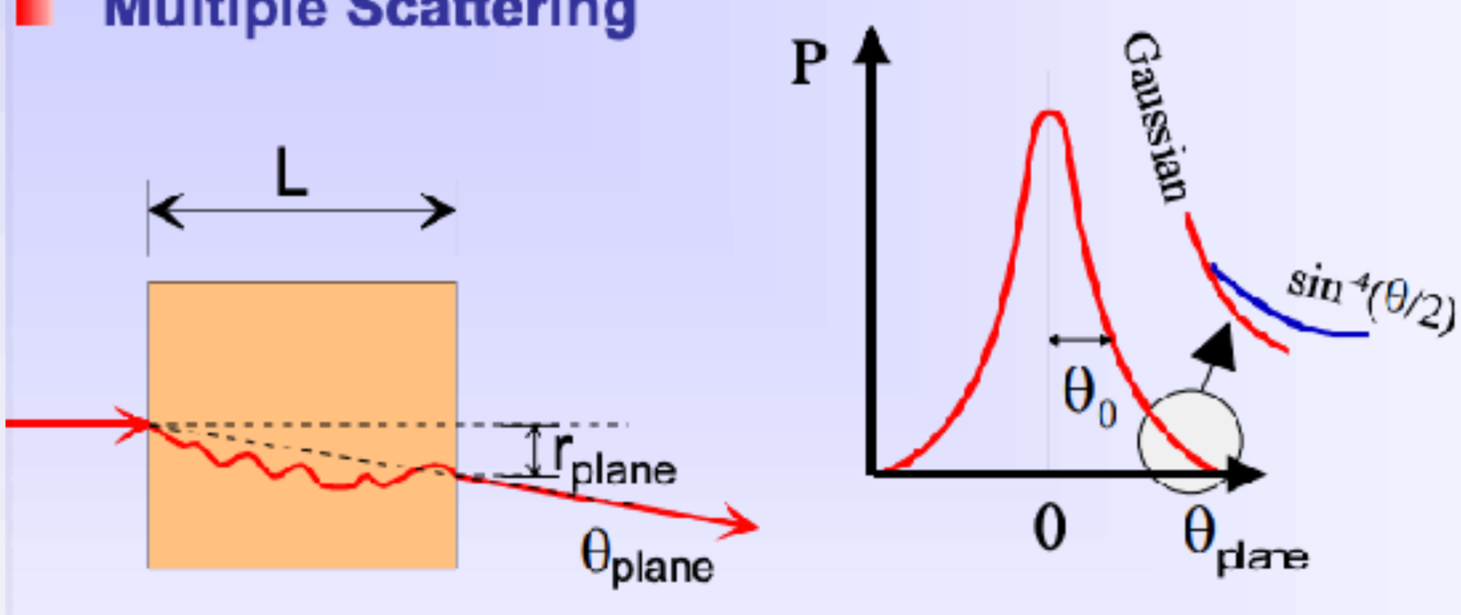


$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4 \theta/2}$$ Rutherford formula

- Approximation
  - Non-relativistic
  - No spins

- Average scattering angle $\langle\theta\rangle = 0$
- Cross-section for $\theta \to 0$ infinite !

Multiple Scattering



- Scattering does not lead to significant energy loss

Heavy Charged Particles

$m \gg m_e$

Includes: muons, tau, mesons, hadrons …

Stopping Power

- *Energy loss through ionization and atomic excitation*

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

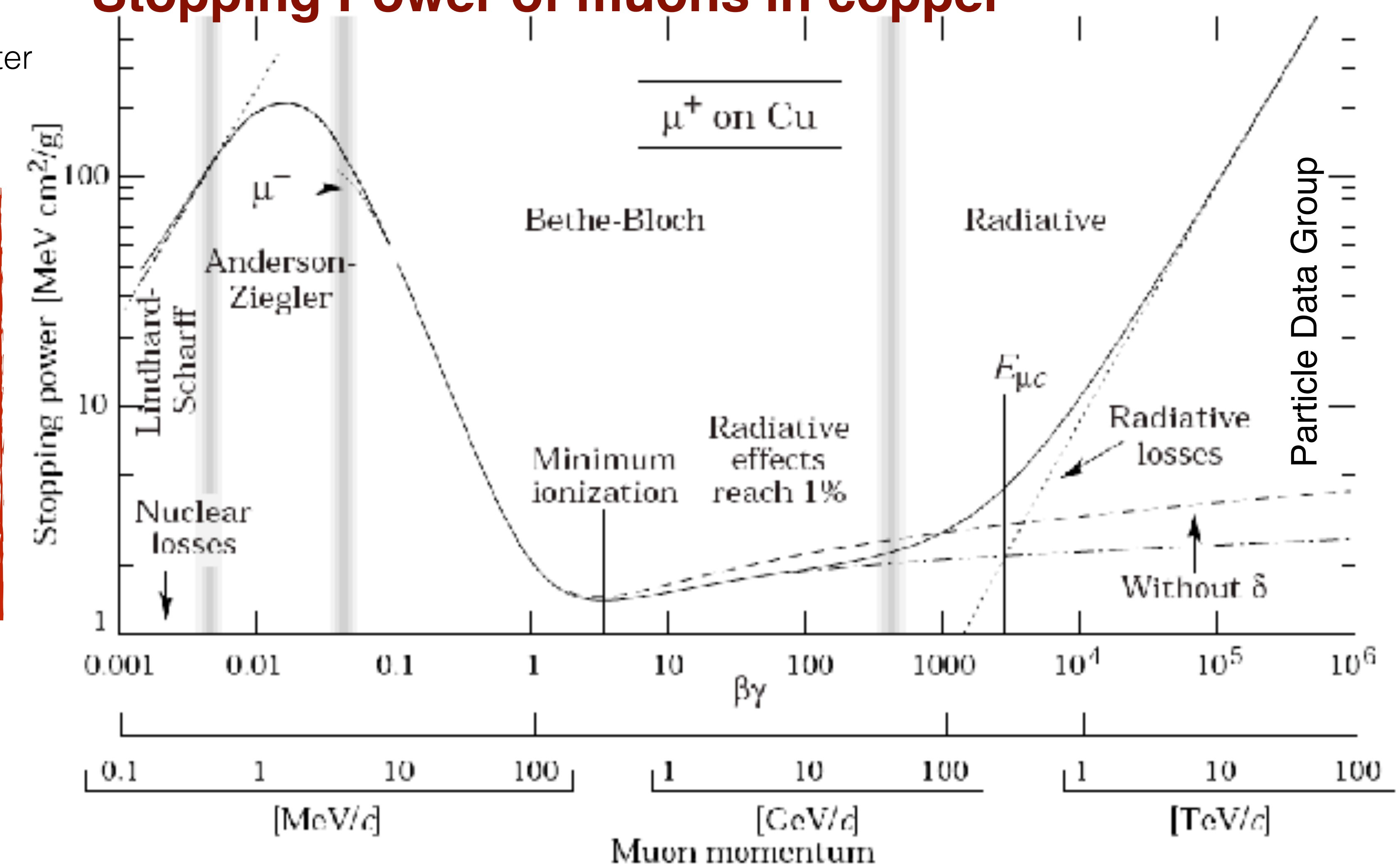
Bethe-Bloch Formula

Energy Loss = Energy lost in matter x density

Linear stopping power (S) is the differential energy loss of the particle in the material divided by the differential path length. Also called the specific energy loss.

$$S = -\frac{dE}{dx}$$

Stopping Power of muons in copper



Stopping Power

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

Valida per $\beta>0.1$

I = potenziale medio di eccitazione

Z, A, ρ = caratteristiche del mezzo

z, β, γ = caratteristiche della particella incidente

W_{max} = massima energia trasferita in una collisione

r_e = raggio classico dell'elettrone $r_e = \frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{m_e c^2}$ ..

M_e = massa dell'elettrone

N_a = N di Avogadro

C = correzione di shell

δ = effetto densità

Stopping Power

La capacità di un dato materiale di frenare una particella carica (stopping power) e' definito come la perdita di energia differenziale della particella nel materiale divisa per la lunghezza percorsa in corrispondenza ad essa:

$$S = -\frac{dE}{dx} = \frac{4\pi e^4}{m_e}\frac{z^2}{v^2}\rho Z\left[\ln\left(\frac{2m_e v^2}{I}\right) - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$$

(Bethe formula)

Proprietà della particella

Proprietà del materiale

v e ze sono la velocità e la carica delle particelle carica pesante incidente
N e Z sono la densità e il numero atomico degli atomi dell'assorbitore
I indica un parametro sperimentale legato all'eccitazione media e al potenziale di ionizzazione

Nota:

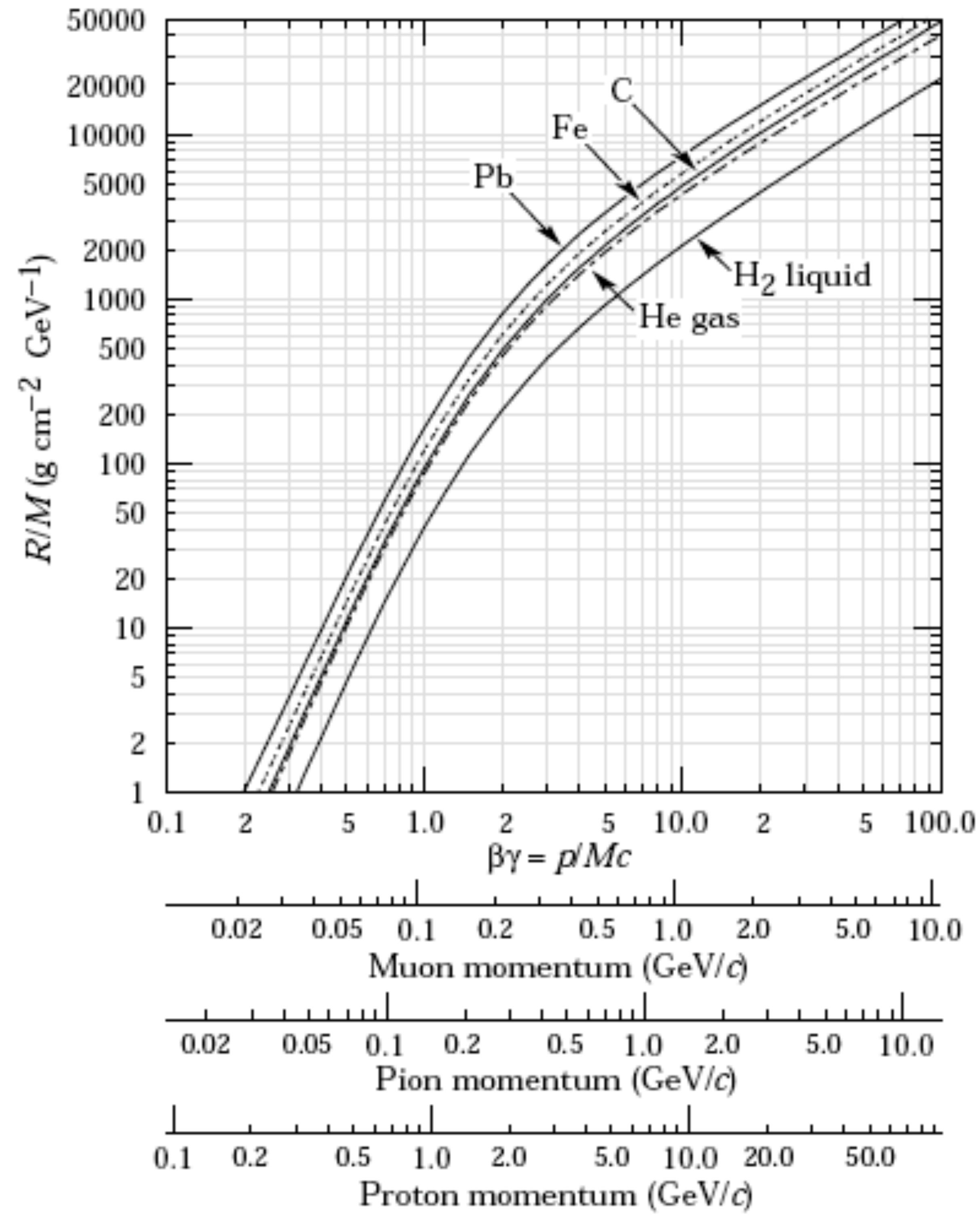
- In primissima approssimazione lo stopping power è proporzionale all'inverso dell'energia della particella carica incidente ($S \propto 1/E$), direttamente proporzionale alla sua carica al quadrato ($S \propto z^2$) e direttamente proporzionale al numero atomico del materiale ($S \propto Z$)
- Quando più la velocità della particella carica pesante è piccola tanto più è lungo il tempo trascorso nelle vicinanze di un atomo e tanto maggiore sarà l'impulso e l'energia trasferita
- Nel termine in parentesi quadra, solo il primo termine e' significativo in regime non relativistico ($v \ll c$)
- A bassa energia la particella carica pesante cattura elettroni dagli atomi e quindi si riduce il termine Ze

Range

- The range is an average quantity.
- The thickness of material that stops a particle.
- Integrate the (stopping power)$^{-1}$ from the Bethe—Bloch formula to obtain the range.

$$R = \int_E^0 \frac{dx}{dE} dE$$

- Useful for low energy hadrons and muons with momenta below a few hundred GeV (MIP)
- Radiative Effects important at higher momenta. Additional effects at lower momenta.



Range

Teilchen	in Luft	in Wasser	in Wasser	in Wasser	in Wasser	in Blei
Impuls	1 MeV	1 MeV	10 MeV	1 GeV	1 TeV	1 TeV
e	3,8 m	4 mm	5 cm			
p	2,3 cm	30 um			5 km	((als mip: 833 m))
alpha	5 mm	6 um	0,1 mm			
muon				50 m	50 km	833 m

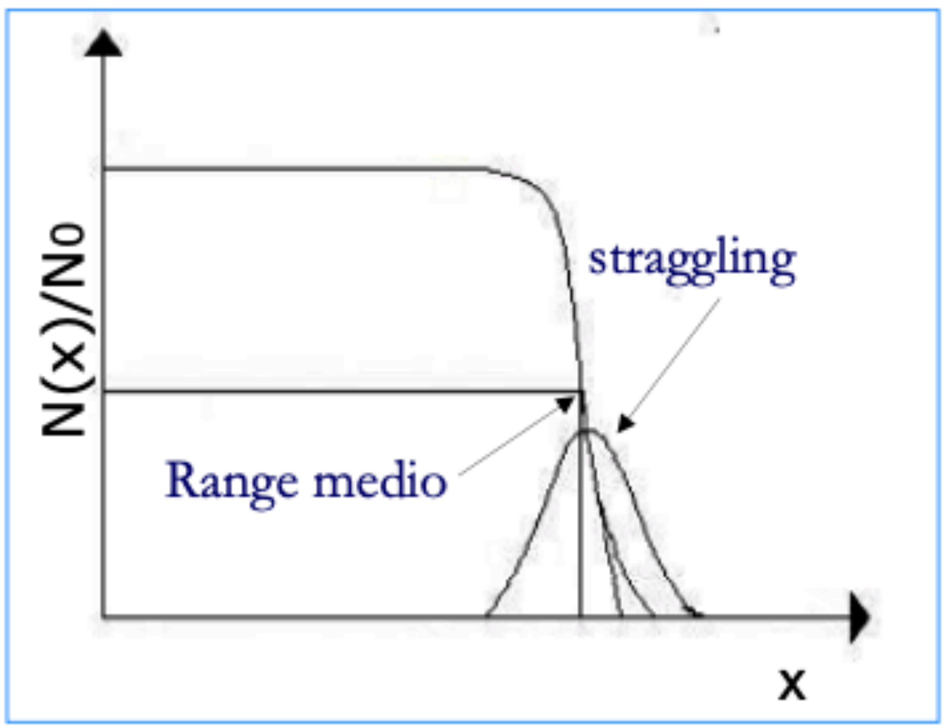
Formule semiempiriche:
Range of alpha in air:
R_{alpha_air}[mm]= $(0.05E_{alpha}+2.85)*E^{(3/2)}$ for $E_{alpha}>4MeV$

Range of protons in air:
R_{proton_air}[m]= $(E_{proton}/9.3)^{(1.8)}$ for $E_{proton}<200MeV$

Straggling

Il processo di perdita di energia di una particella carica in un materiale è di natura statistica. Se un numero di particelle con la stessa energia attraversa un mezzo, avranno una distribuzione statistica di ranges intorno ad un valor medio, che in prima approssimazione ha forma gaussiana.

Bethe-Bloch: <dE/dx> = *valor medio* della perdita di energia in uno strato di materia per ionizzazione



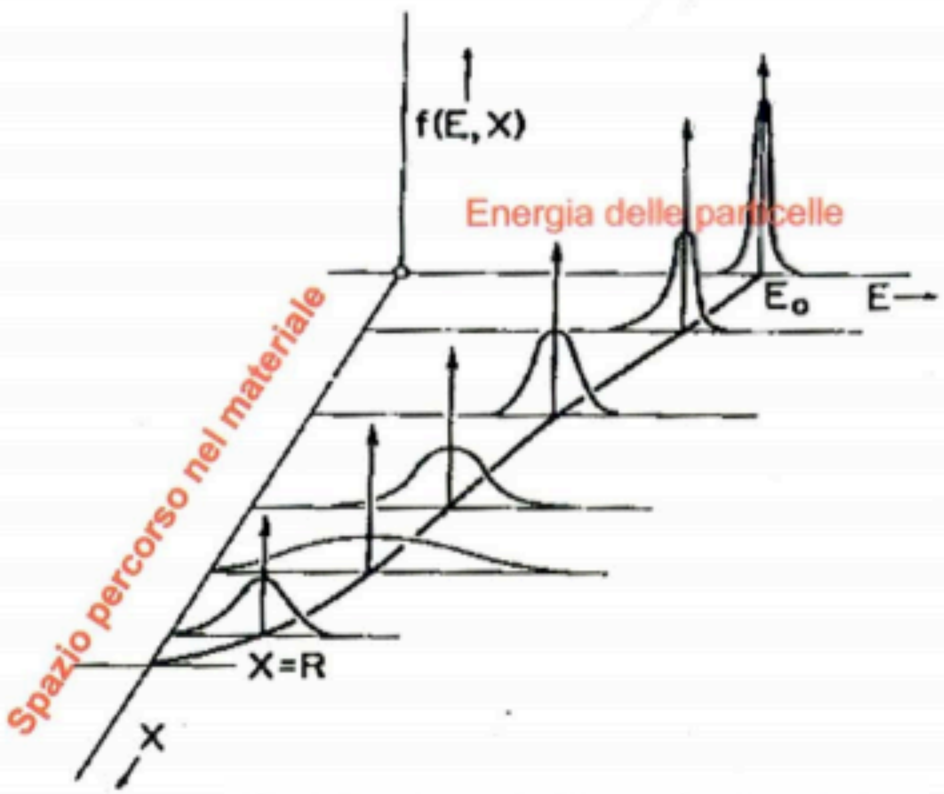
Fluttuazioni statistiche su:

- **Numero di collisioni subite**
- **Energia trasferita per ogni collisione**

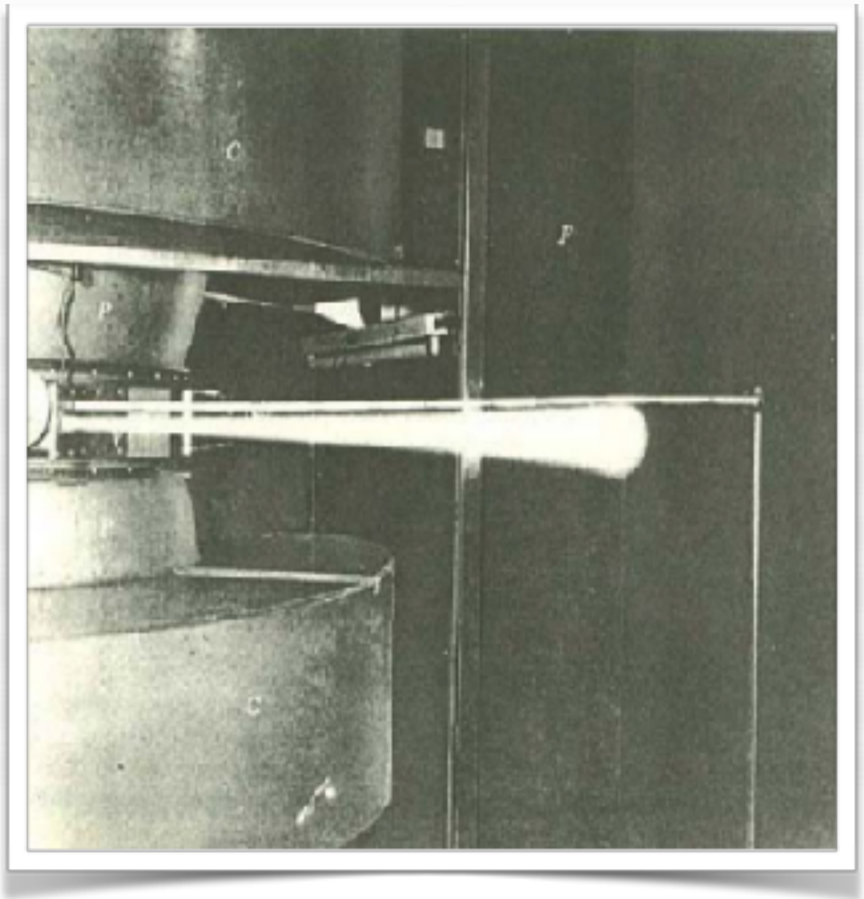
Straggling

In un fascio di particelle cariche pesanti monocromatiche all'interno di un materiale, l'energia delle particelle e' caratterizzata quindi da una distribuzione di probabilità con un valor medio ed una deviazione standard e/o larghezza a metà altezza.

La larghezza a metà altezza della distribuzione di energia varia con la distanza percorsa dalla particella all'interno del materiale assorbente ed è una misura dello straggling



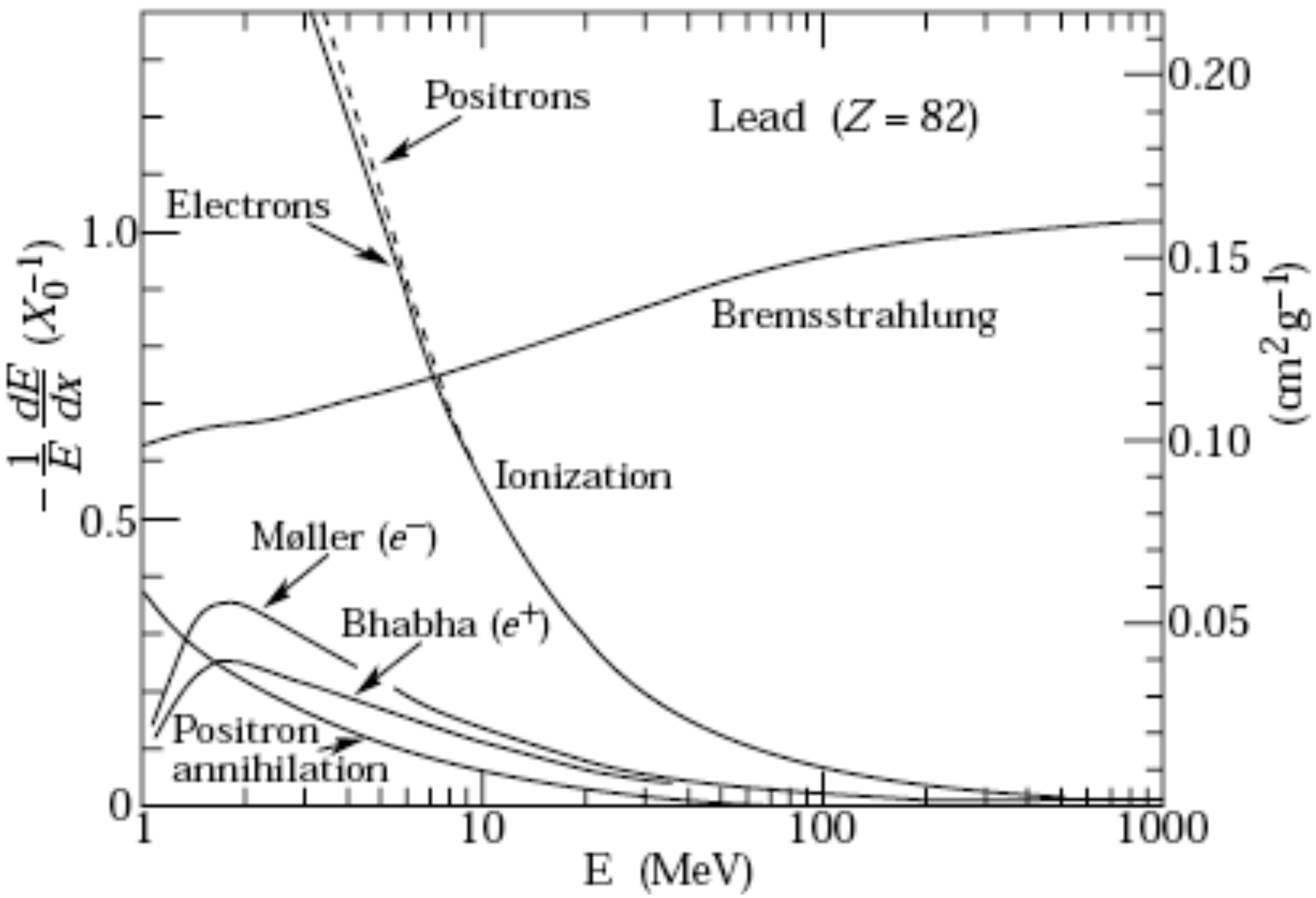
Distribuzione dell'enegia rilasciata da una particella monoenergetica in funzione della distanza di penetrazione



Electrons

Electron Energy Loss

Energy Loss in Lead (normalized)



* *E' sempre derivato dalla relazione di Bethe, e sostanzialmente ha lo stesso andamento. Assumono più importanza i termini relativistici, associati alla contrazione delle lunghezze*

Radiation Length

Mean distance over which an electron loses all but 1/e of its energy.

Electron Energy Loss

Termine Collisionale per l'elettrone
(inelastic impact ionization (+Moeller and Bhabba scattering))

$$S = -\frac{dE}{dx} = \frac{2\pi e^4}{m_e}\frac{1}{v^2}\rho Z\left[\ln\left(\frac{2m_e v^2 E}{2I^2\left(1-\frac{v^2}{c^2}\right)}\right) - \ln 2\left[2\sqrt{\left(1-\frac{v^2}{c^2}\right)} - 1 + \frac{v^2}{c^2}\right] + \left(1-\frac{v^2}{c^2}\right) + \frac{1}{8}\left(1-\sqrt{1-\frac{v^2}{c^2}}\right)^2\right]$$

proprietà dell'elettrone incidente

Termini relativistici

Proprietà del materiale

Dove:

v è la velocità dell'elettrone incidente
N e **Z** sono la densità e il numero atomico degli atomi dell'assorbitore
I indica un parametro sperimentale legato all'eccitazione media e al potenziale di ionizzazione

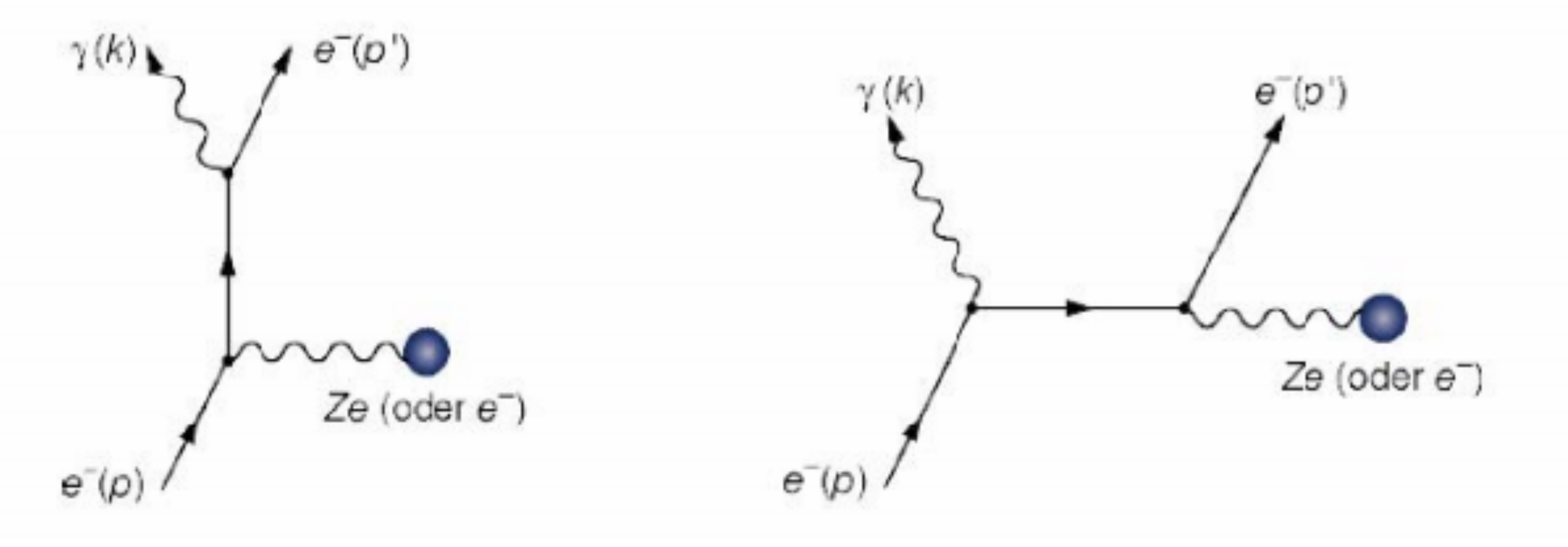
Nota:

- In primissima approssimazione lo stopping power è direttamente proporzionale al numero atomico del materiale ($S \propto Z$)
- Quanto più la velocità dell'elettrone è piccola tanto più è lungo il tempo trascorso nelle vicinanze di un atomo e tanto maggiore sarà l'impulso e l'energia trasferita
- Nel termine in parentesi quadra solo il primo termine e' significativo in regime non relativistico (v<<c)

Bremsstrahlung

* A charged particle of mass M and charge q is deflected by a nucleus of charge Ze (charge partially shielded by electrons)

* The deflection accelerates the charge and therefore it radiates➔ bremsstrahlung



Presence of nucleus required for the conservation of energy and momentum

Beachte:

$$\boxed{-\left(\frac{dE}{dx}\right)_{rad} \propto E \quad \text{und} \quad -\left(\frac{dE}{dx}\right)_{rad} \propto \frac{1}{m^2}}$$

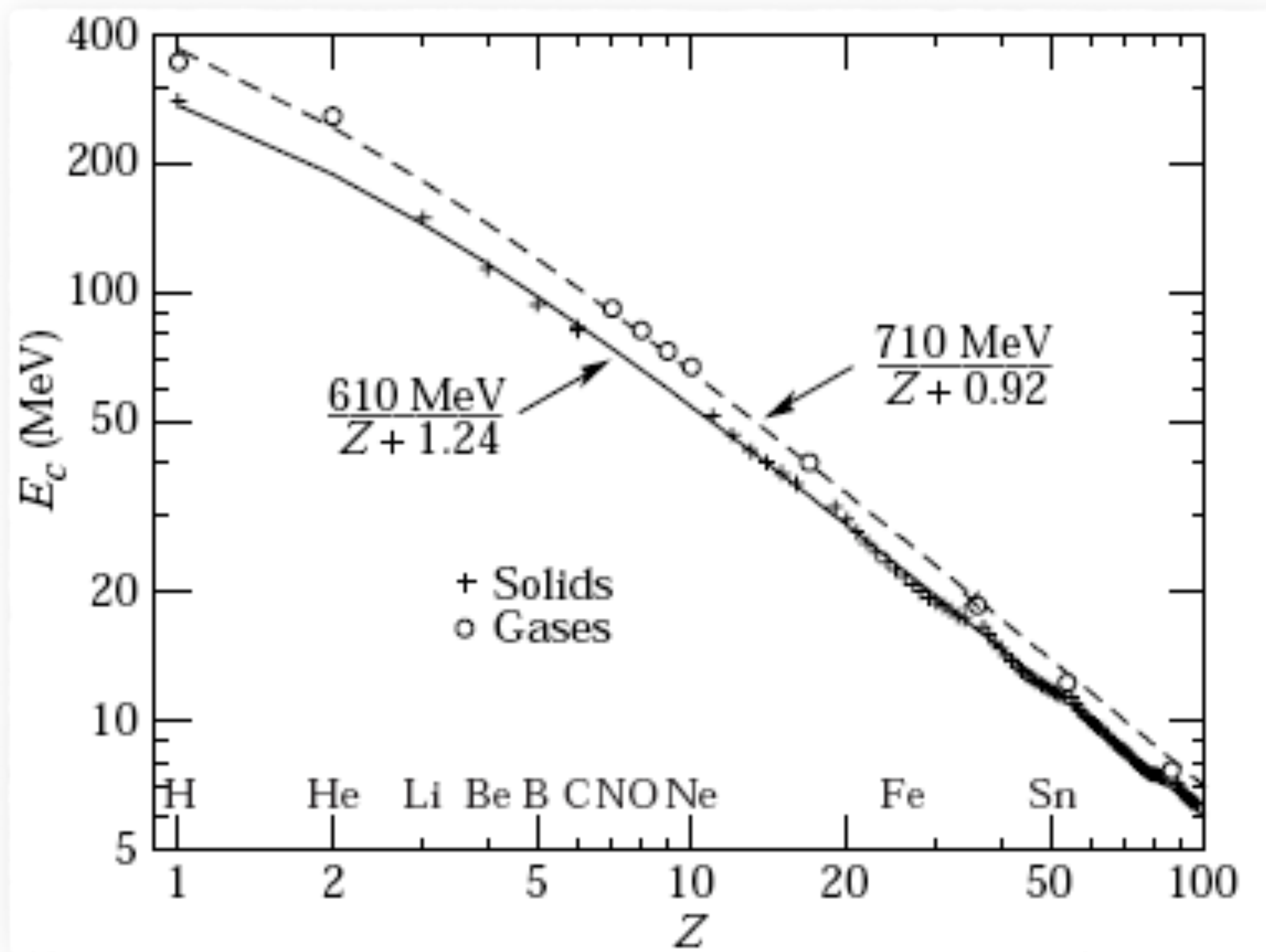
Attenzione, gia per il muone (seconda particella piu leggera) la perdita di energia d'ovuto alla Bremsstrahlung e 40000 volte piu piccola rispetto al elettrone

Electron Critical Energy

- Energy loss through bremsstrahlung is proportional to the electron energy
- Ionization loss is proportional to the logarithm of the electron energy
- Critical energy (Ec) is the energy at which the two loss rates are equal

$$E_c = \frac{800\mathrm{MeV}}{Z+1.2}$$

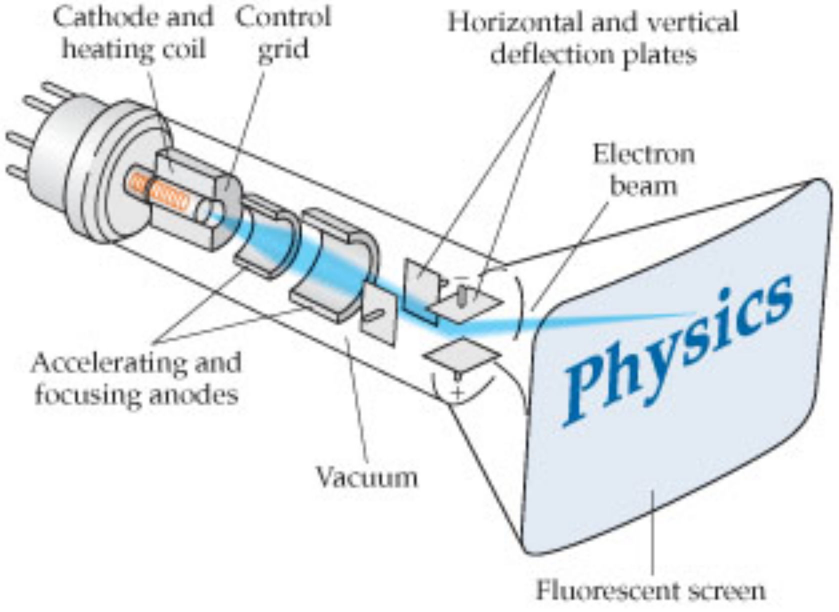
Electron in Copper: E_c = 20 MeV
Muon in Copper: E_c = 400 GeV!



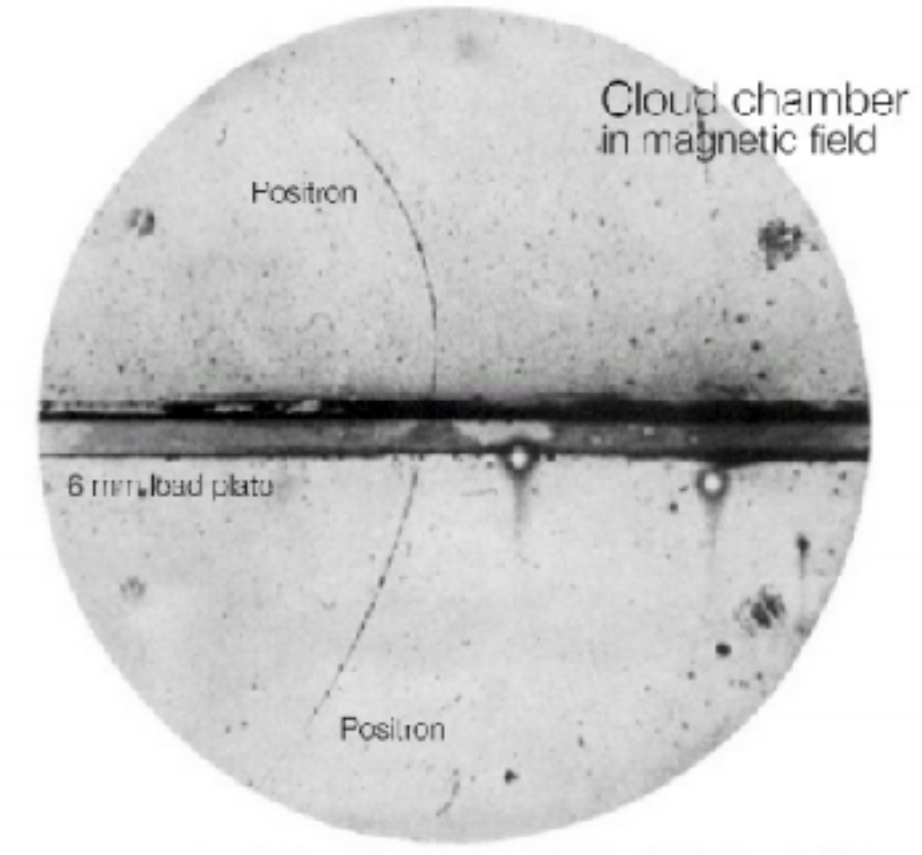
Detection:
Tracking Detectors

Tracking Detectors

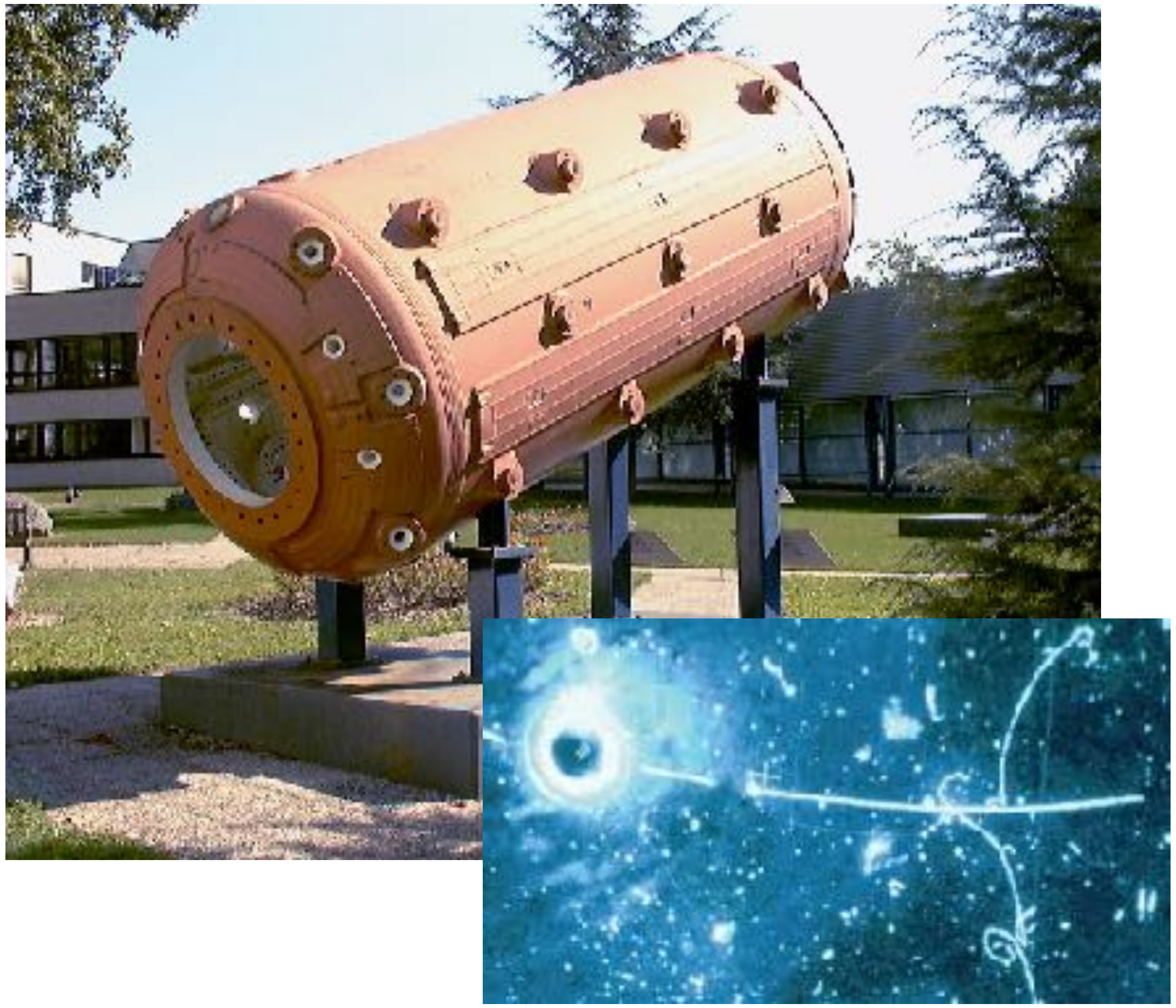
* Based on detecting ionisation caused by passage of the particle
* Different ways of doing it
* In common: Tracking detectors has fine granularity, low energy deposition and are often in a magnetic field



Bubble and Cloud Chamber

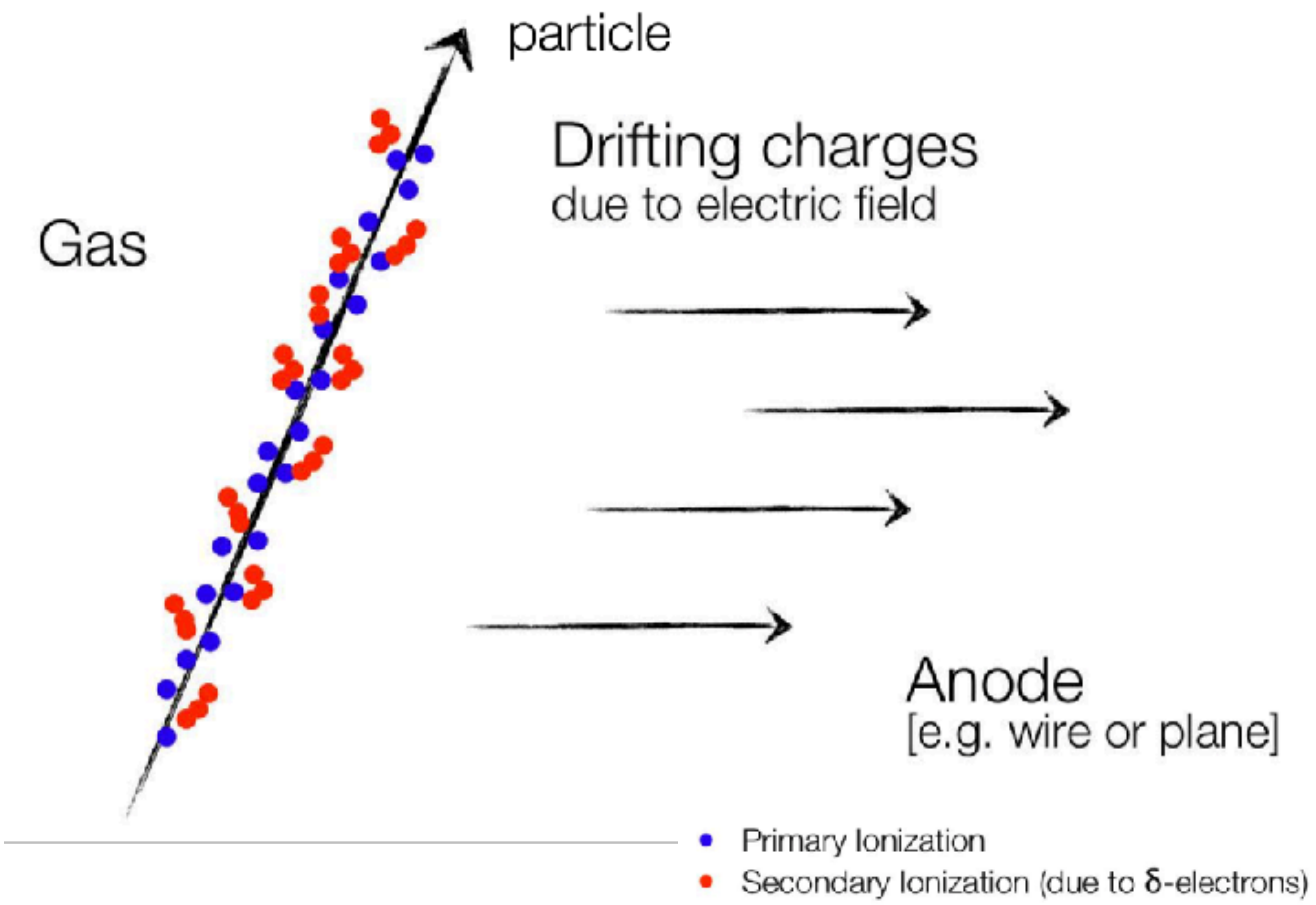


liquid heated to just below its boiling point, decreasing pressure it become metastable. Bubbles forms around ionisation points.



A supersaturated vapor of water or alcohol that form tiny drops around ionised molecules (condensation centers)

Gas Detectors



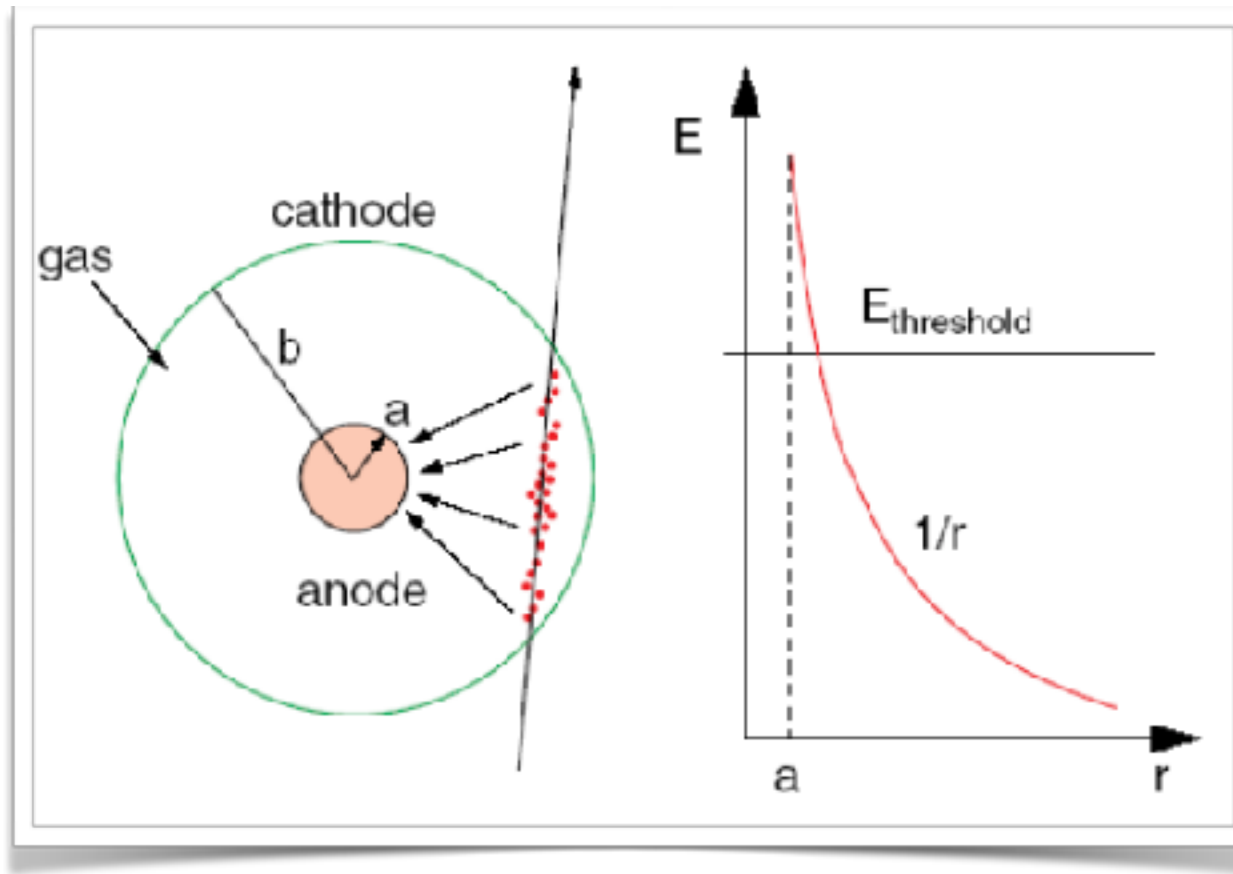
Gas Detectors

- Electrons liberated by ionization drift towards the anode wire.

- Electrical field close to the wire (typical wire Ø ~few tens of μm) is sufficiently high for electrons (above 10 kV/cm) to gain enough energy to ionize further

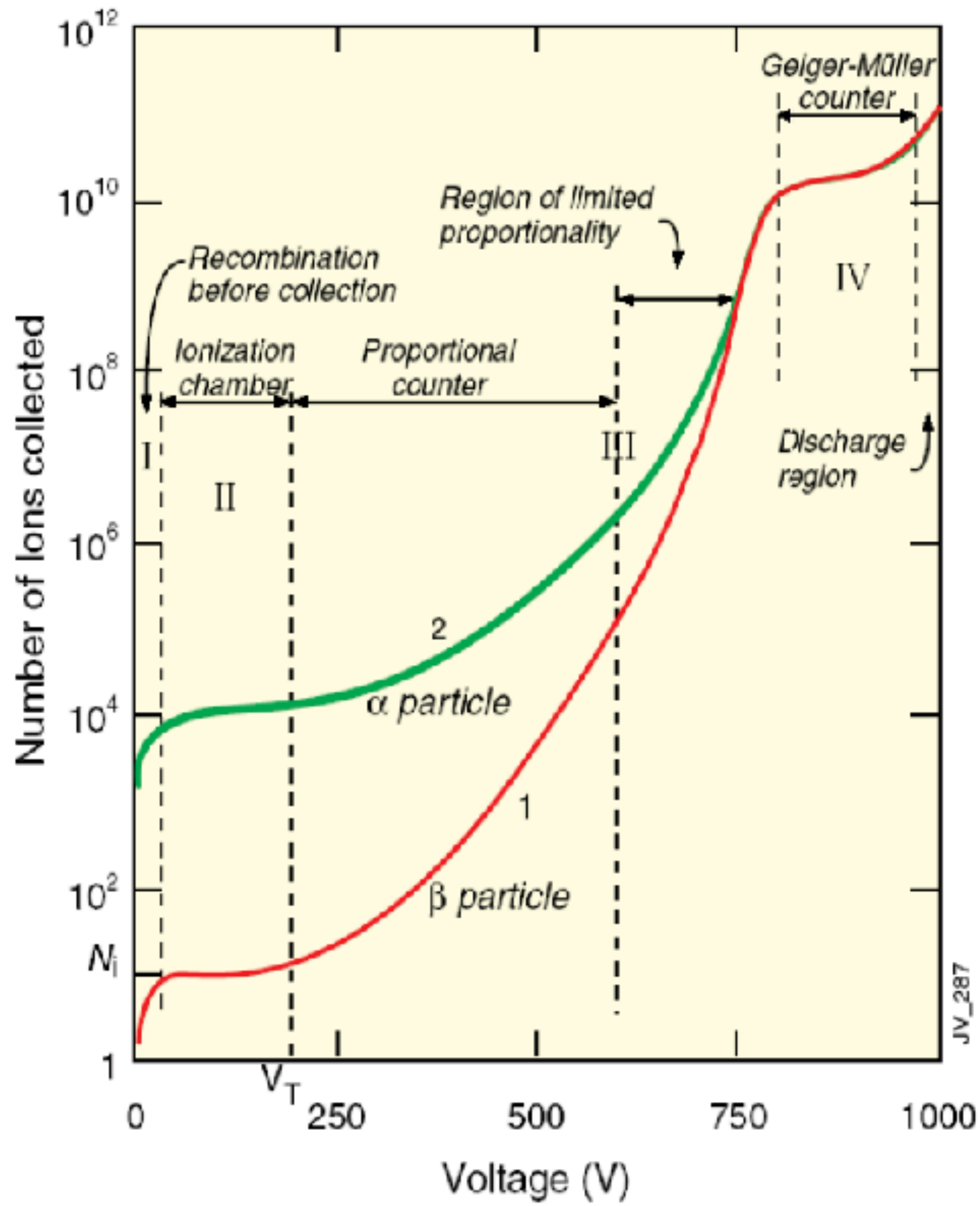
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r} \qquad V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

- Avalanche – exponential increase of number of electron ion pairs.



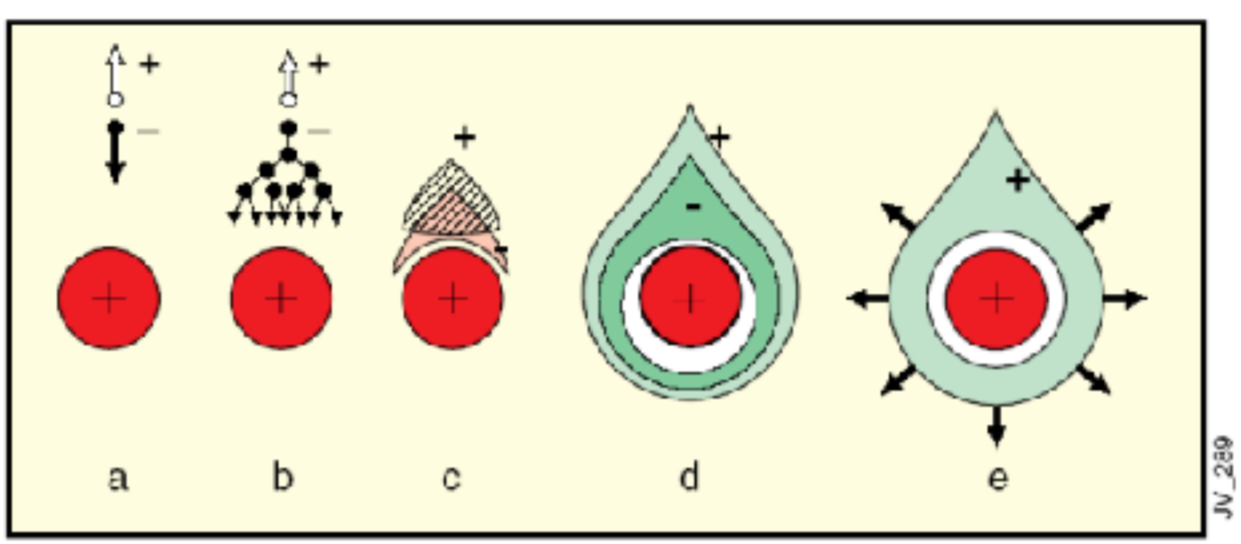
Gas Detectors

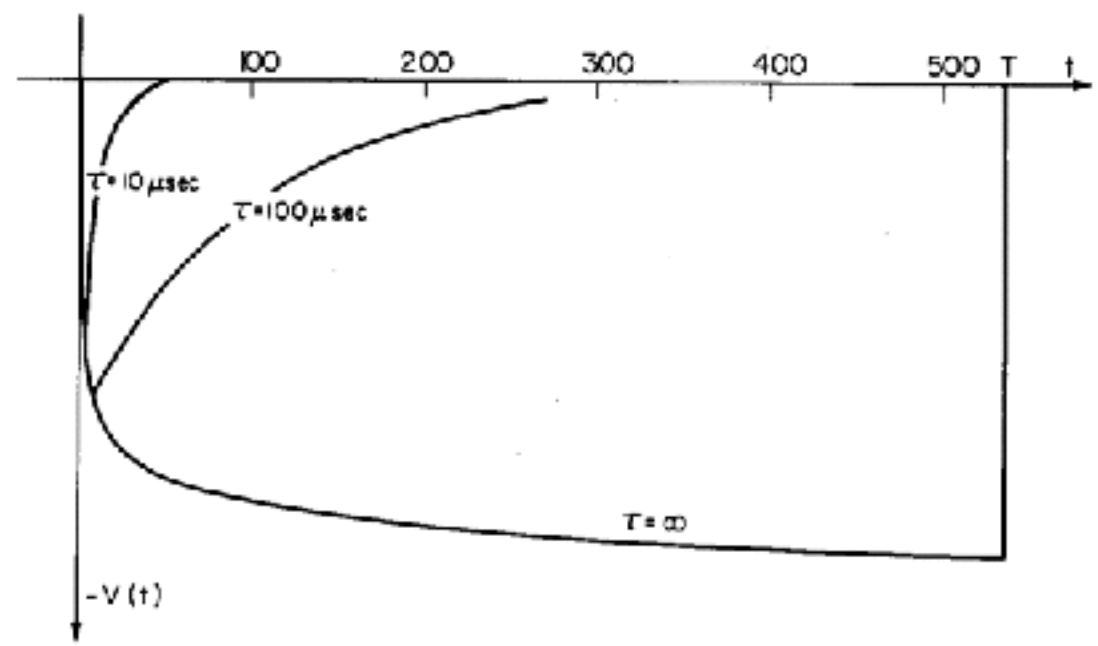
- **ionization mode** – full charge collection, but no charge multiplication; gain ~ 1
- **proportional mode** – multiplication of ionization starts;
  - signal proportional to original ionization → possible energy measurement (dE/dx);
  - secondary avalanches have to be quenched; gain ~ 10^4 – 10^5
- **limited proportional mode** (saturated, streamer) – strong photoemission;
  - secondary avalanches merging with original avalanche;
  - requires strong quenchers or pulsed HV; Large signals → simple electronics; gain ~ 10^{10}
- **Geiger mode** – massive photoemission;
  - full length of the anode wire affected; discharge stopped by HV cut; strong quenchers needed as well



Signal Formation

* Avalanche formation within a few wire radii and within t < 1 ns!
* Signal induction both on anode and cathode due to moving charges (both electrons and ions).
* Electrons collected by anode wire, i.e. dr is small (few μm). Electrons contribute only very little to detected signal (few %).
* Ions have to drift back to cathode

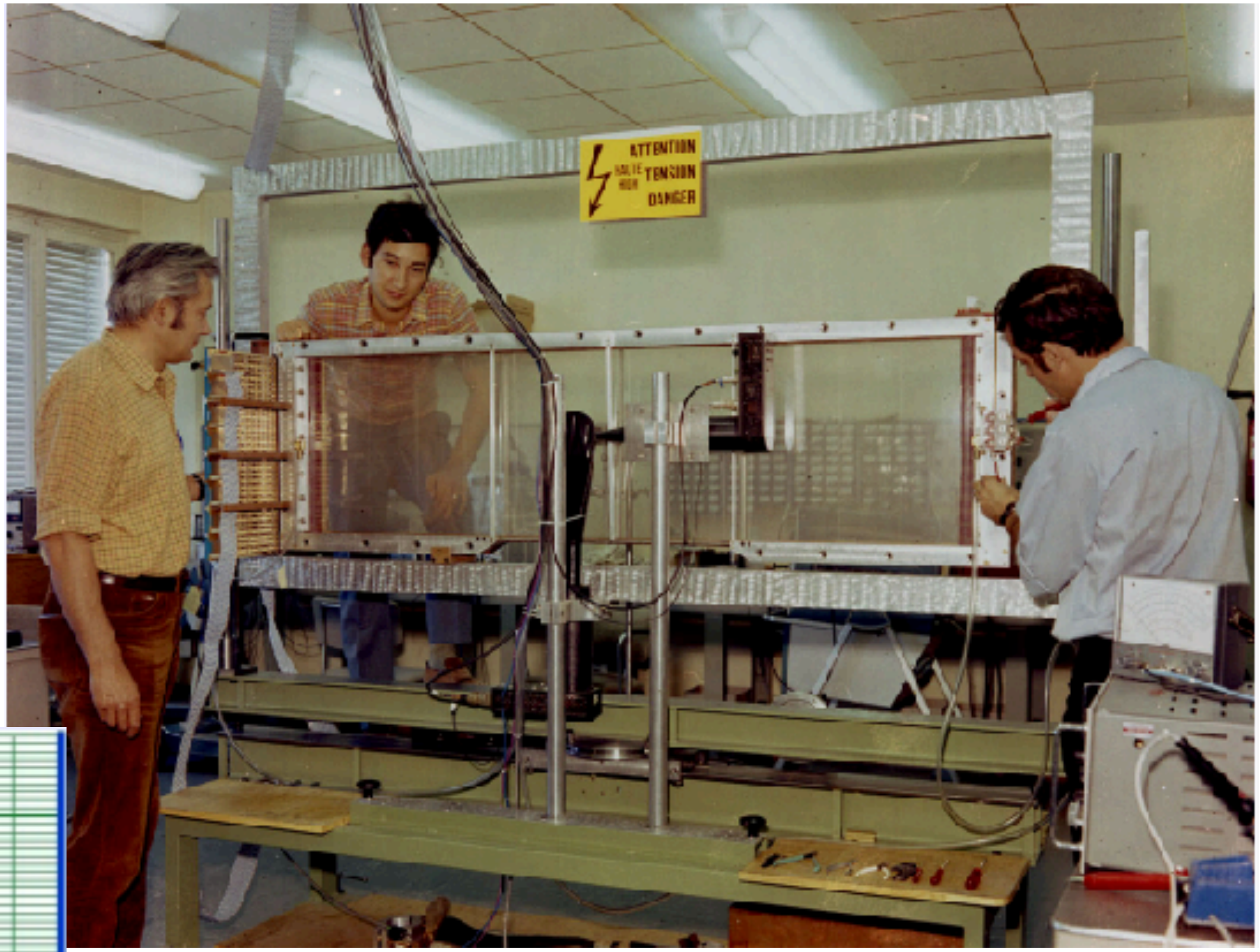


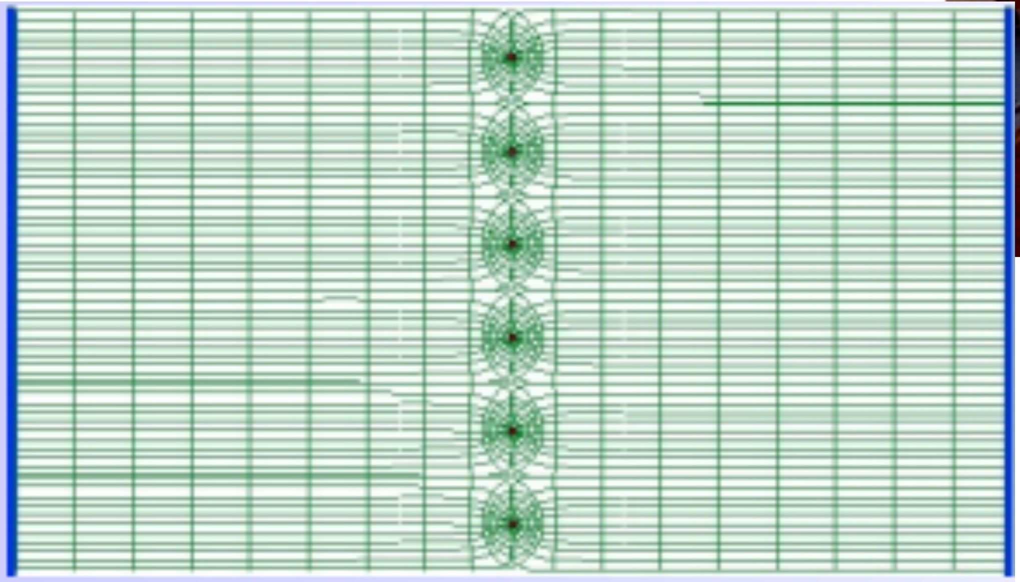


Multiwire Proportional Chamber

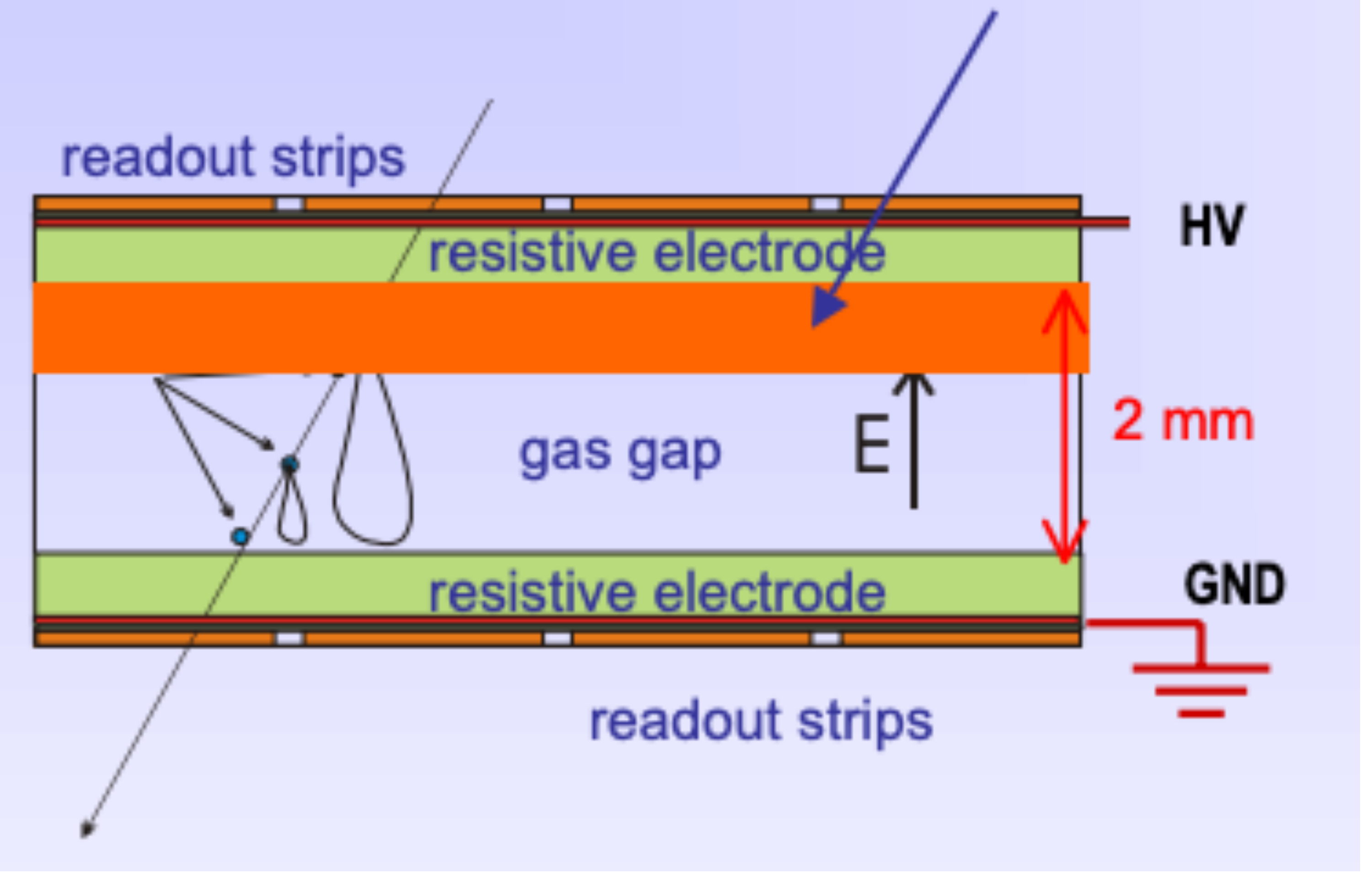
Typical geometry

- between plates 5mm
- 1mm between wires,
- radius 20 μm





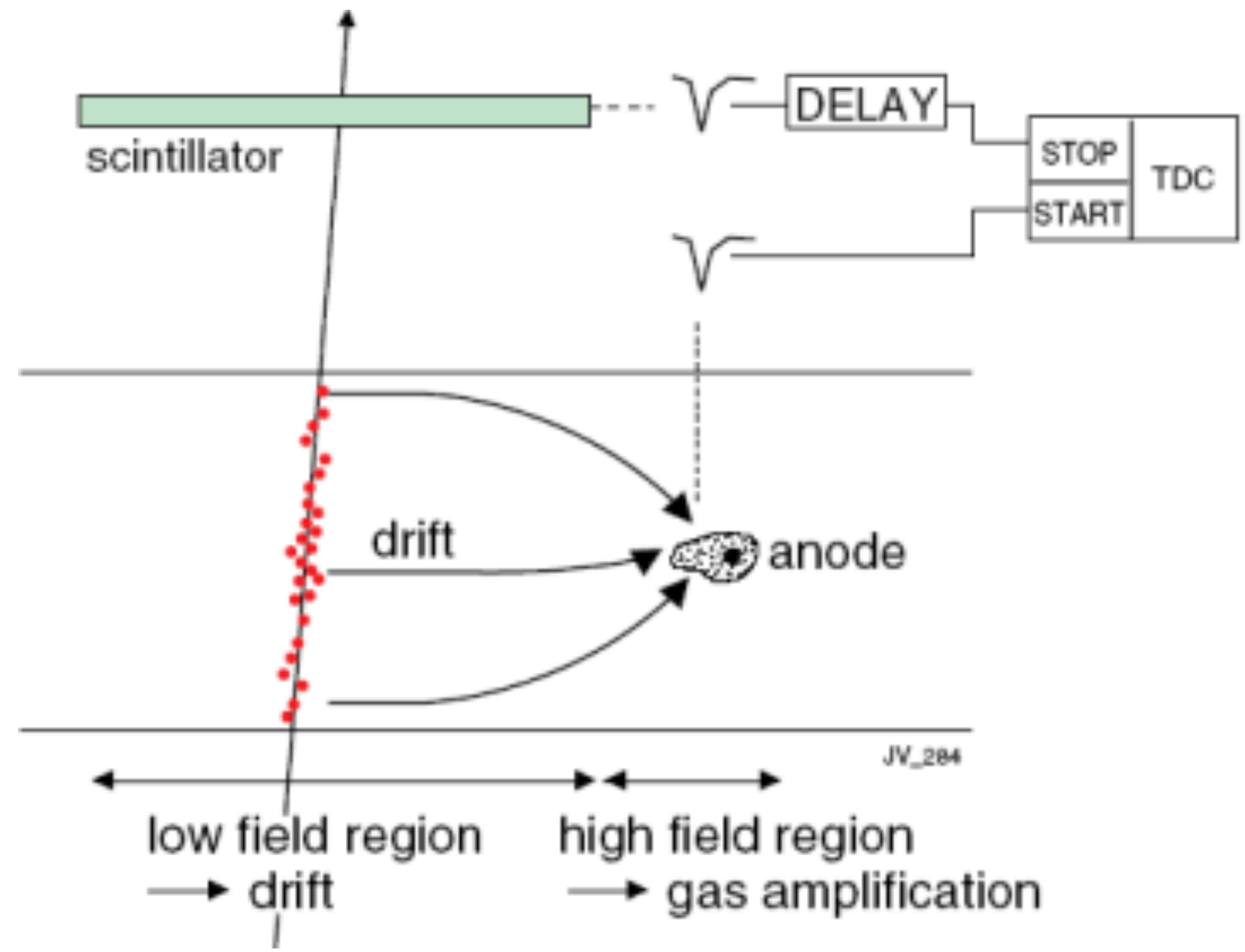
RPC - Resistive Plate Chamber



exceptional time resolution suited for the trigger applications

Drift Chambers

* Measure arrival time of electrons at sense wire relative to a time t_0.
* Need a trigger (bunch crossing or scintillator).
* Drift velocity independent from E.



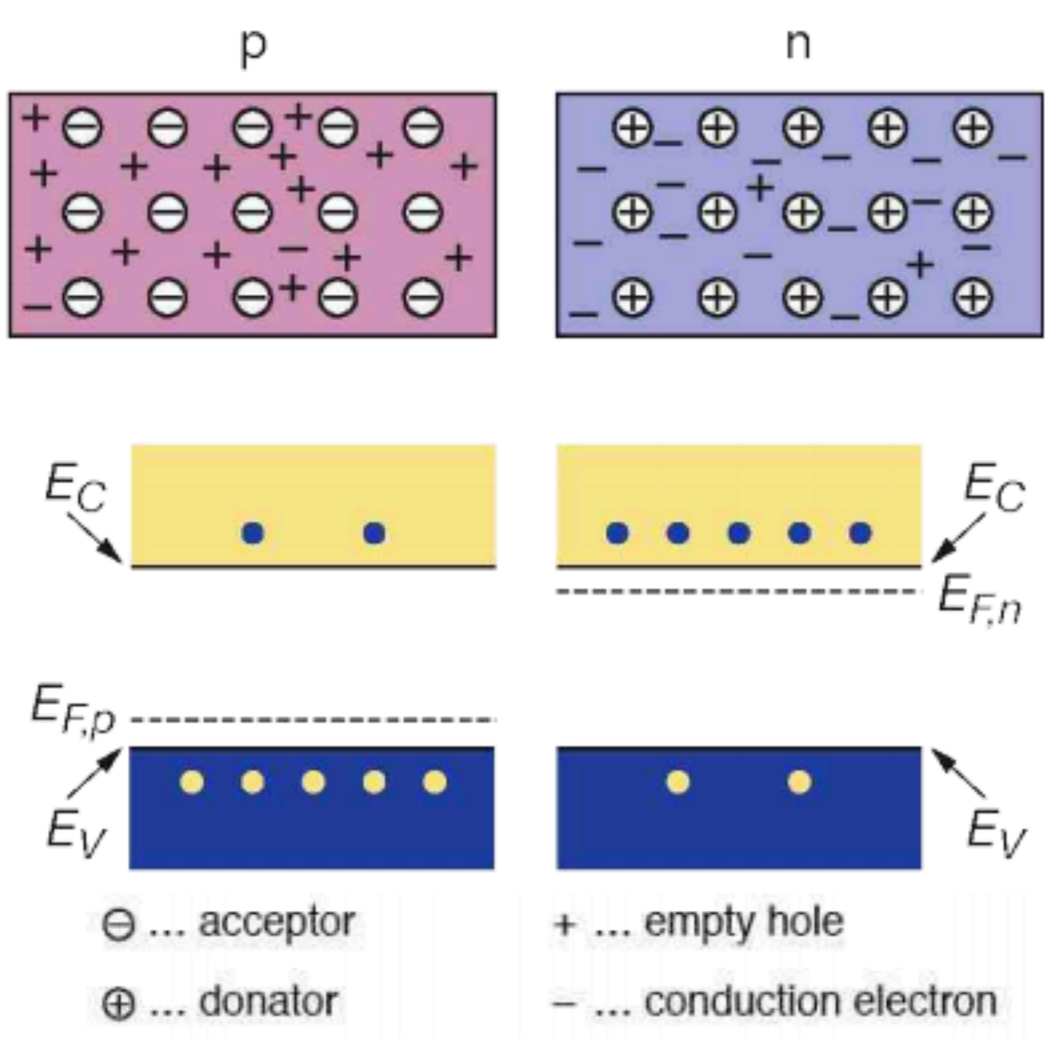
Resolution determined by diffusion, primary ionization statistics, path fluctuations and electronics

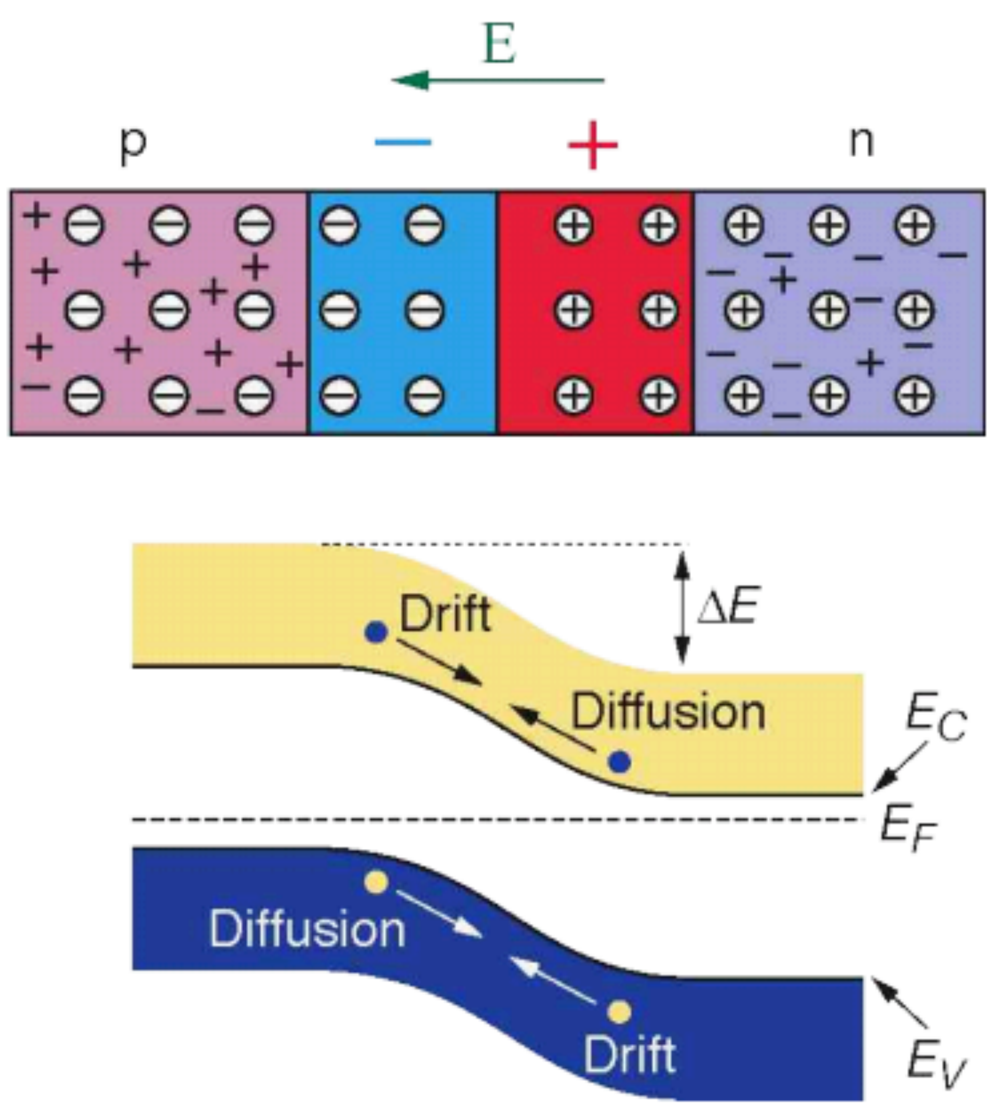
Gas Detectors in LHC Experiments

ALICE:	TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)
ATLAS:	TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)
CMS:	Muon detector (drift tubes, CSC), RPC (muon trigger)
LHCb:	Tracker (straw tubes), Muon detector (MWPC, GEM)
TOTEM:	Tracker & trigger (CSC , GEM)

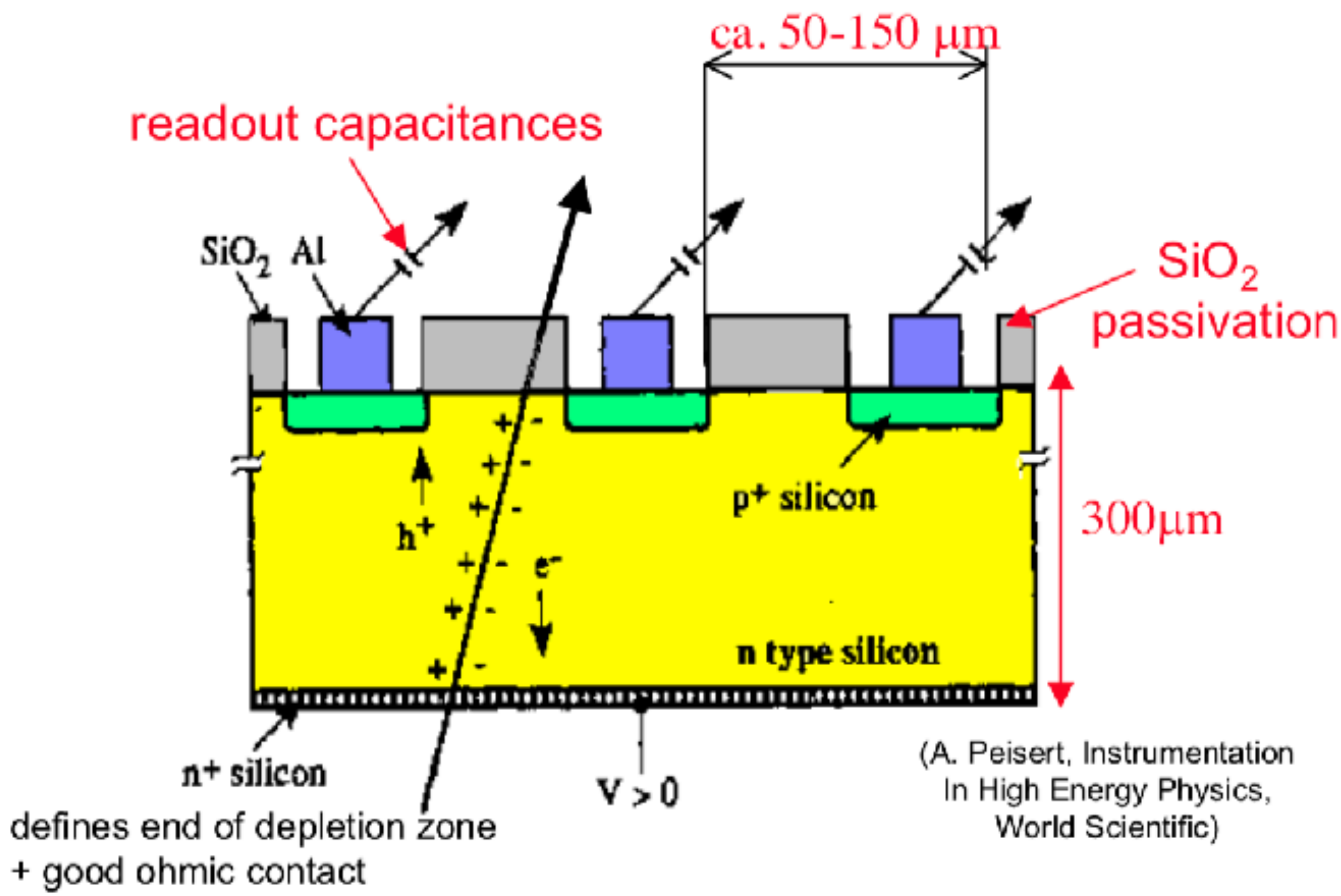
Silicon Detectors

* Between n-type and p-type semiconductor a stable region free of charge carries is created and is called the depletion zone





Silicon Detectors



High granularity, very sensible, low voltage,
high price for large coverage
Used in high track density regions

Last Lesson Summary

Ionisation VS Bremsstrahlung

Bethe-Bloch Formula

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$$-\left\langle\frac{dE}{dx}\right\rangle_{el.} = K\frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{m_e\beta^2c^2\gamma^2T}{2I^2} + F(\gamma)\right]$$

[T: kinetic energy of electron]

$W_{max} = ½T$

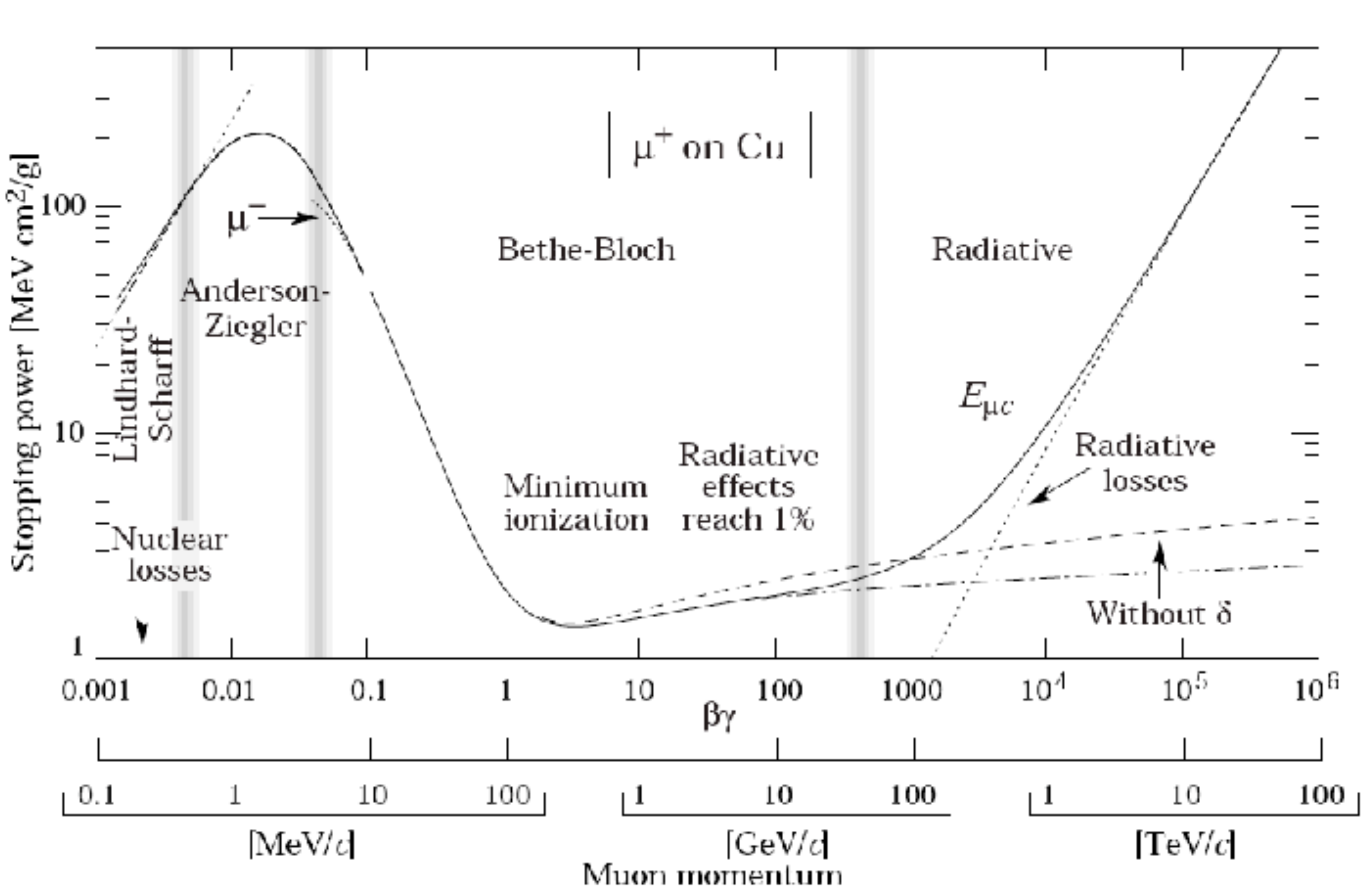
* $\propto Z$
* $\propto \ln(E)$
* Basse energie/impulsi

$$-\left\langle\frac{dE}{dx}\right\rangle \approx \frac{4N_a Z^2\alpha^3(\hbar c)^2}{m_e^2c^4} E \ln\frac{183}{Z^{1/3}}$$

* $\propto Z^2$
* $\propto E/m^2$
* Alte energie/impulsi

Heavy Charged

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$



Electrons

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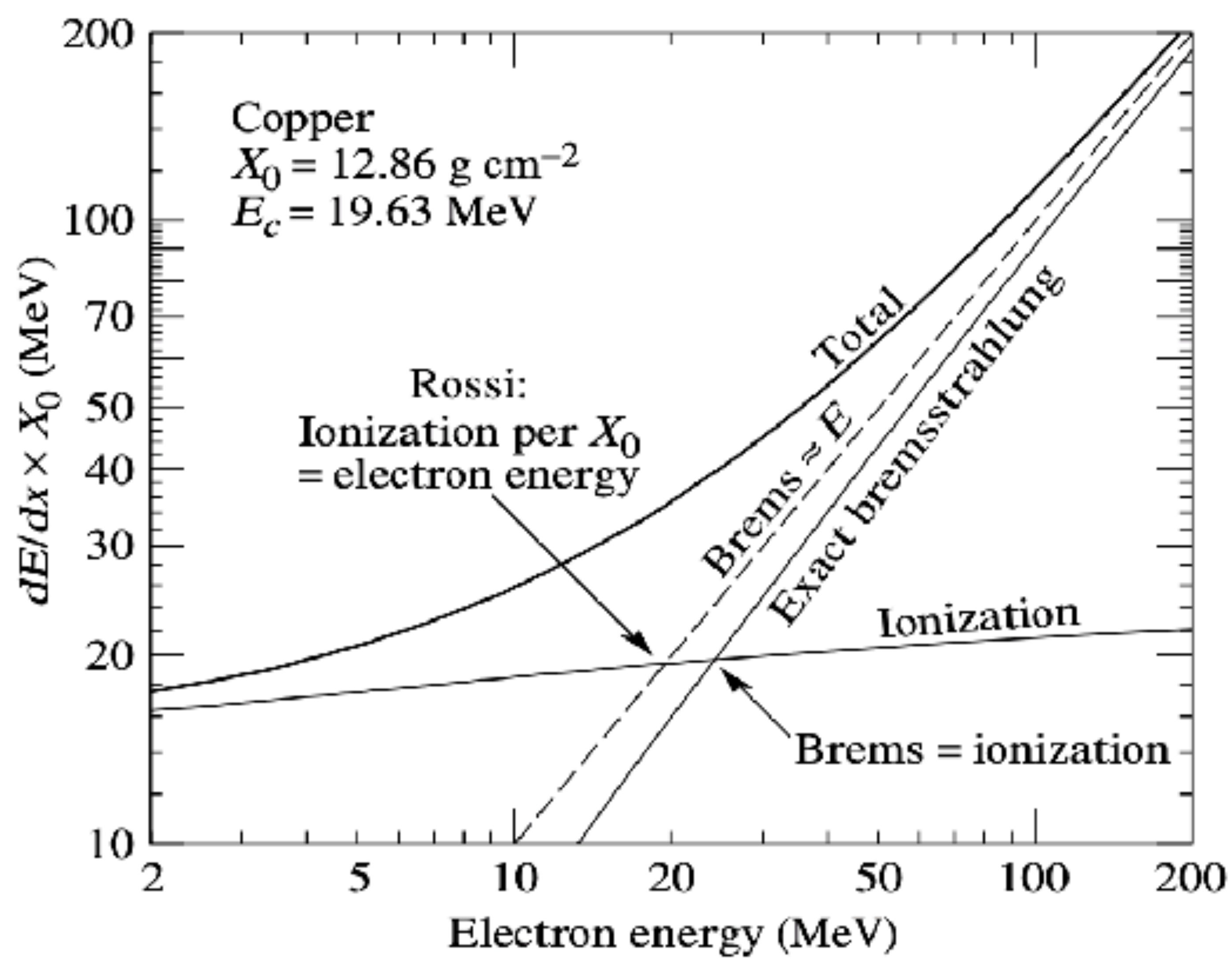

Critical Energy

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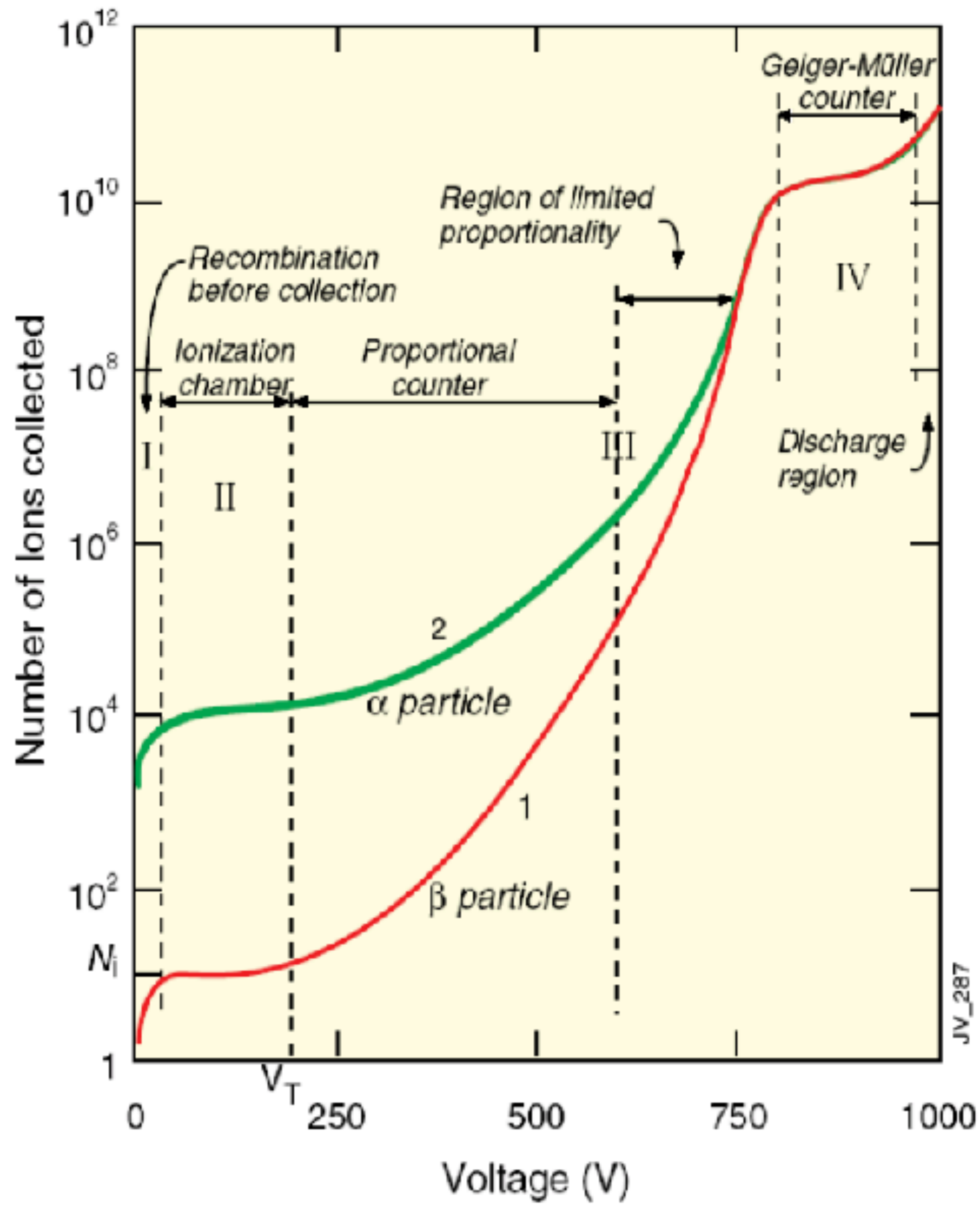
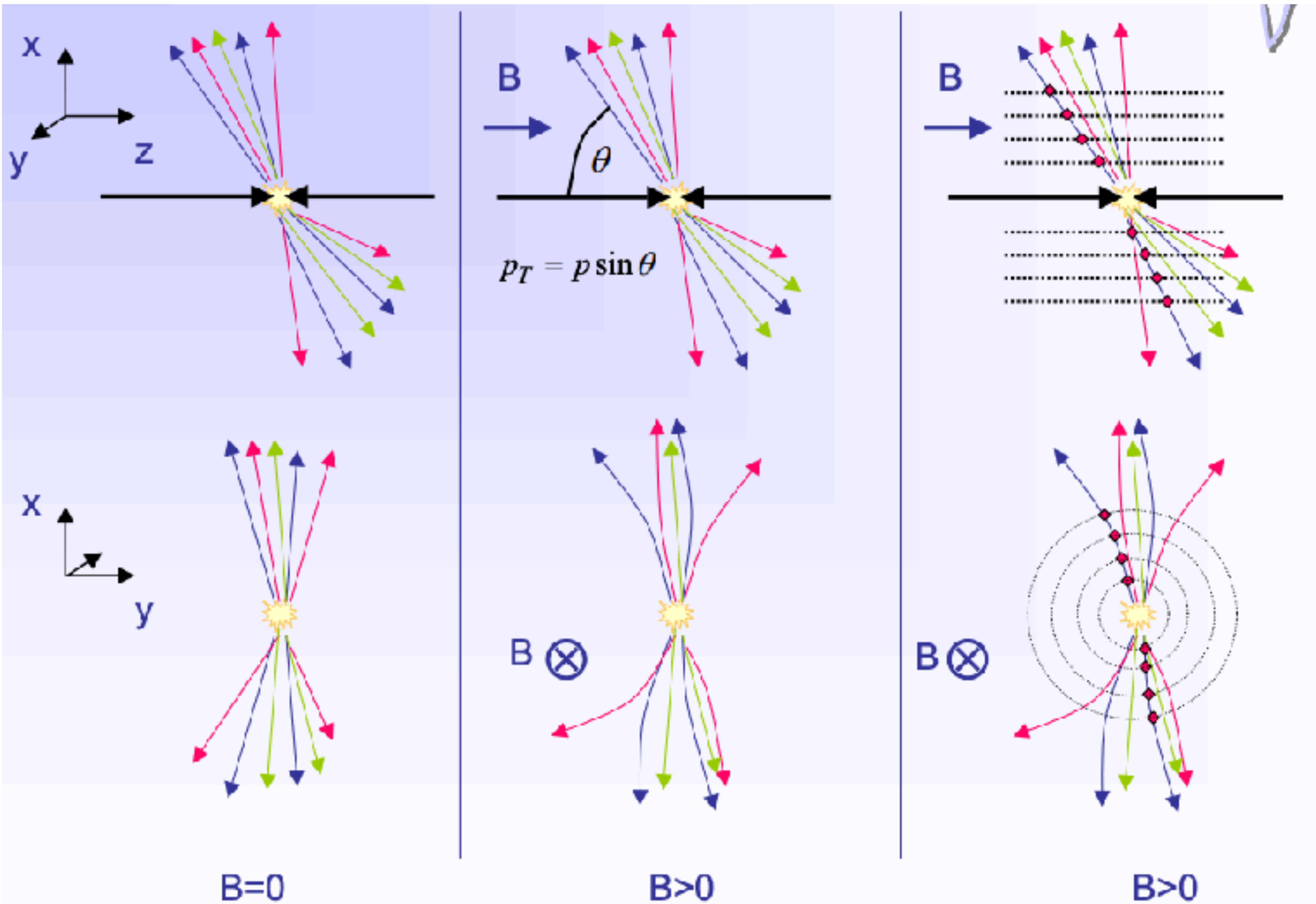


Tracker Comparison

* Multiwire chamber:
  * resolution ~0,5 mm
  * time ~10 ns (quite fast)
* RPC:
  * fast!
  * No great spatial resolution
  * Used as trigger
* Drift Chamber:
  * high resolution ~40 μm
  * expansive!
  * Good at low rate
*

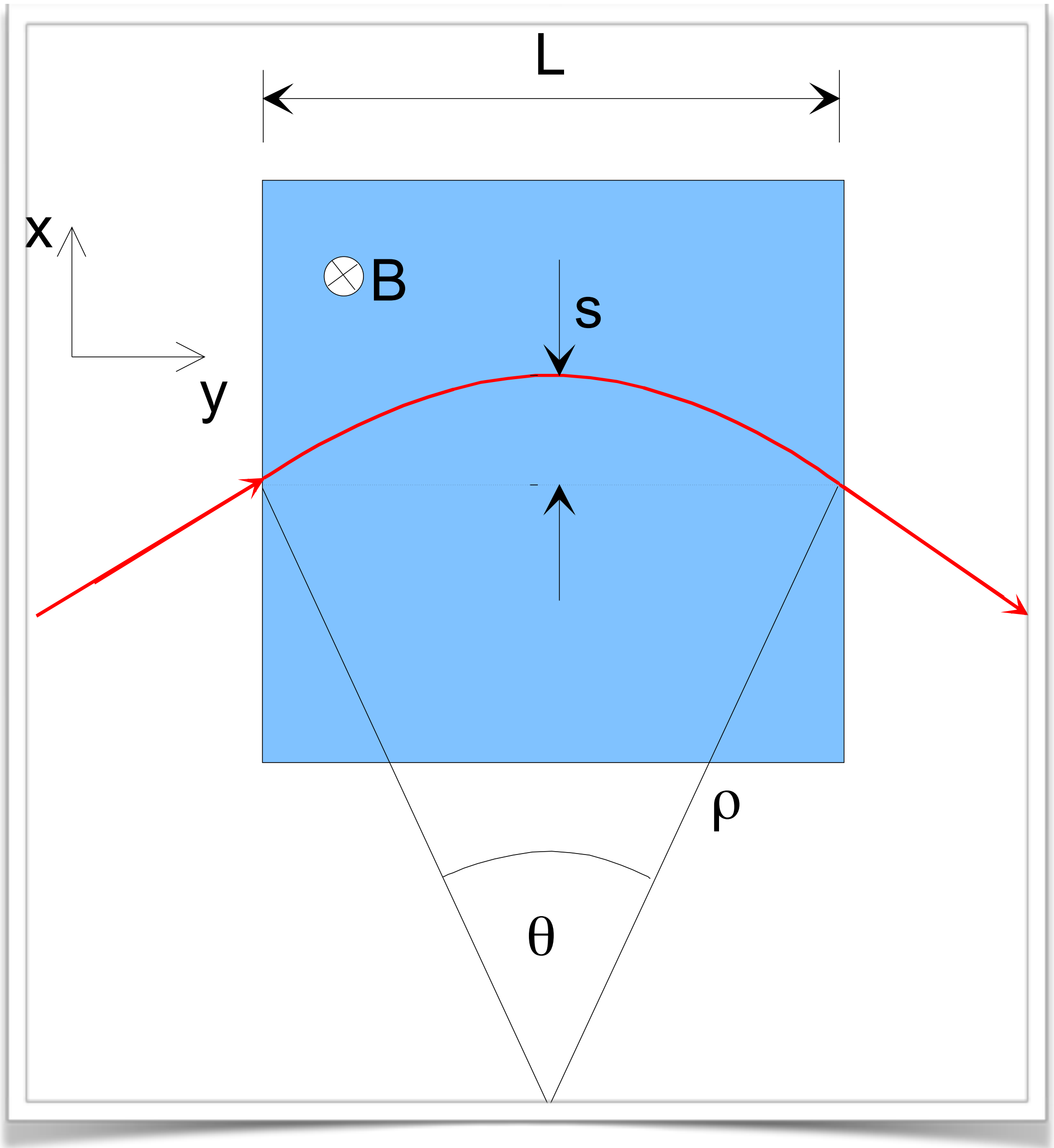
Momentum Measurement

Momentum Measurement



Momentum Measurement

$$\frac{mv^2}{\rho} = q(v \times B) \quad \rightarrow \quad p_T = qB\rho \qquad\qquad p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T \cdot m})$$



$$\frac{L}{2\rho} = \sin\theta/2 \approx \theta/2 \quad \rightarrow \quad \theta \approx \frac{0.3L \cdot B}{p_T}$$

$$s = \rho(1-\cos\theta/2) \approx \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2 B}{p_T}$$

For the simple case of three measurements:

$s = x_2 - (x_1 + x_3)/2 \Rightarrow ds = dx_2 - dx_1/2 - dx_3/2$

with $\sigma_x \approx dx_i$ uncorrelated error of single measurement:

$$\sigma_s^2 = \sigma_x^2 + \frac{\sigma_x^2}{4} \cdot 2 = \frac{3}{2}\sigma_x^2$$

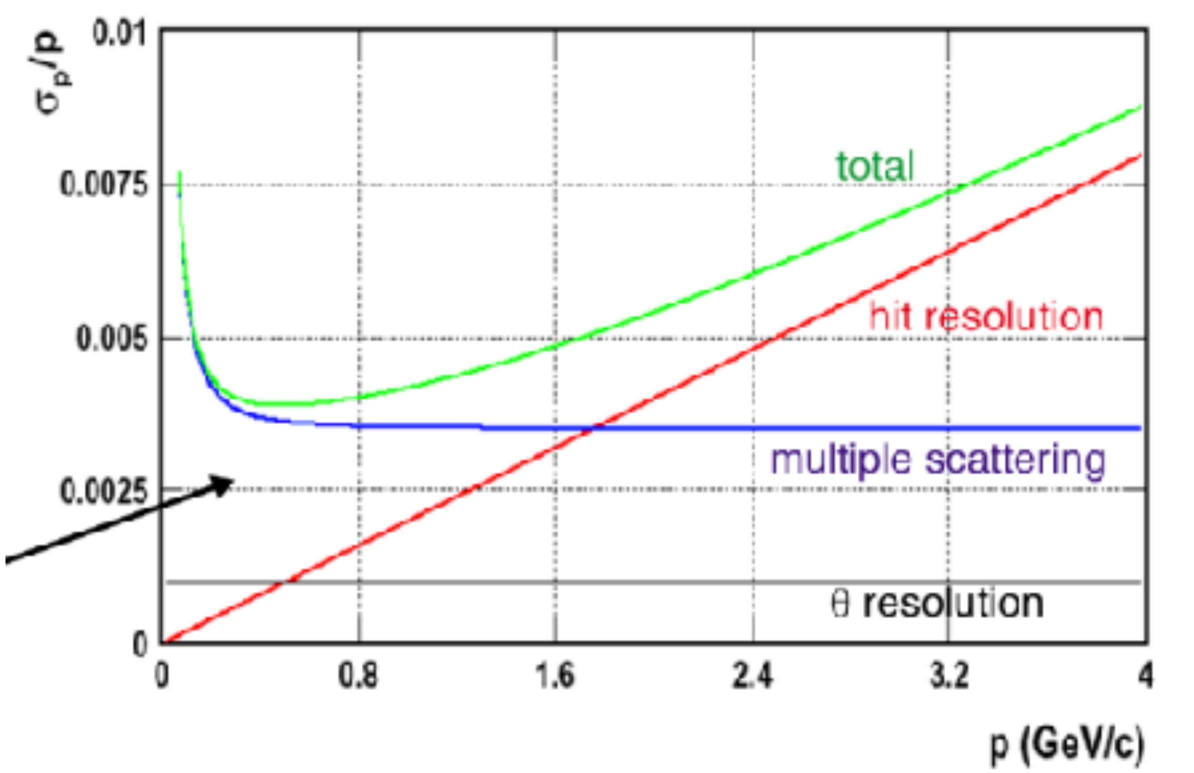
Momentum Resolution

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\sigma_x \cdot \frac{8p_T}{0.3BL^2}$$

- degrades linearly with transverse momentum
- improves linearly with increasing B field
- improves quadratically with radial extension of detector

$$\boxed{\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}}$$

In the case of N equidistant measurements



Adding the contribution of the multiple scattering

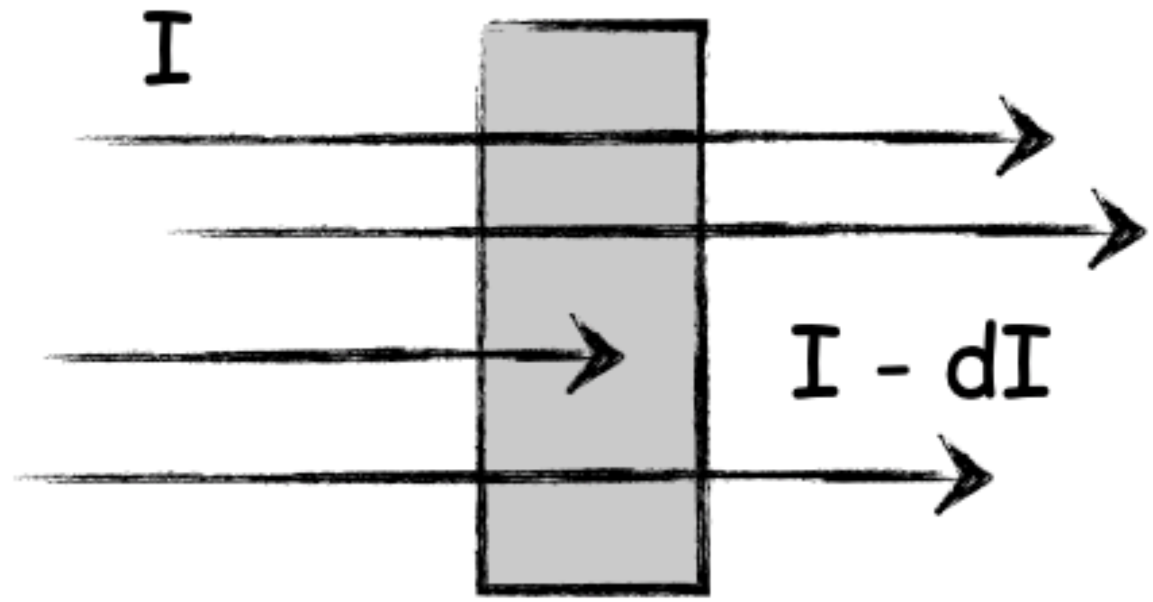
$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\sqrt{\frac{720}{N+4}}\frac{\sigma_x p\sin\theta}{0.3BL^2}\right)^2 + \left(\frac{0.2}{\beta B\sqrt{LX_0}\sin\theta}\right)^2$$

Photons & electrons

Interaction of photons with matter

Characteristic for interactions of photons with matter:

A single interaction removes photon from beam !



$$dI = -\mu\, I\, dx$$

[μ : absorption coefficient]

depends on E, Z, ρ

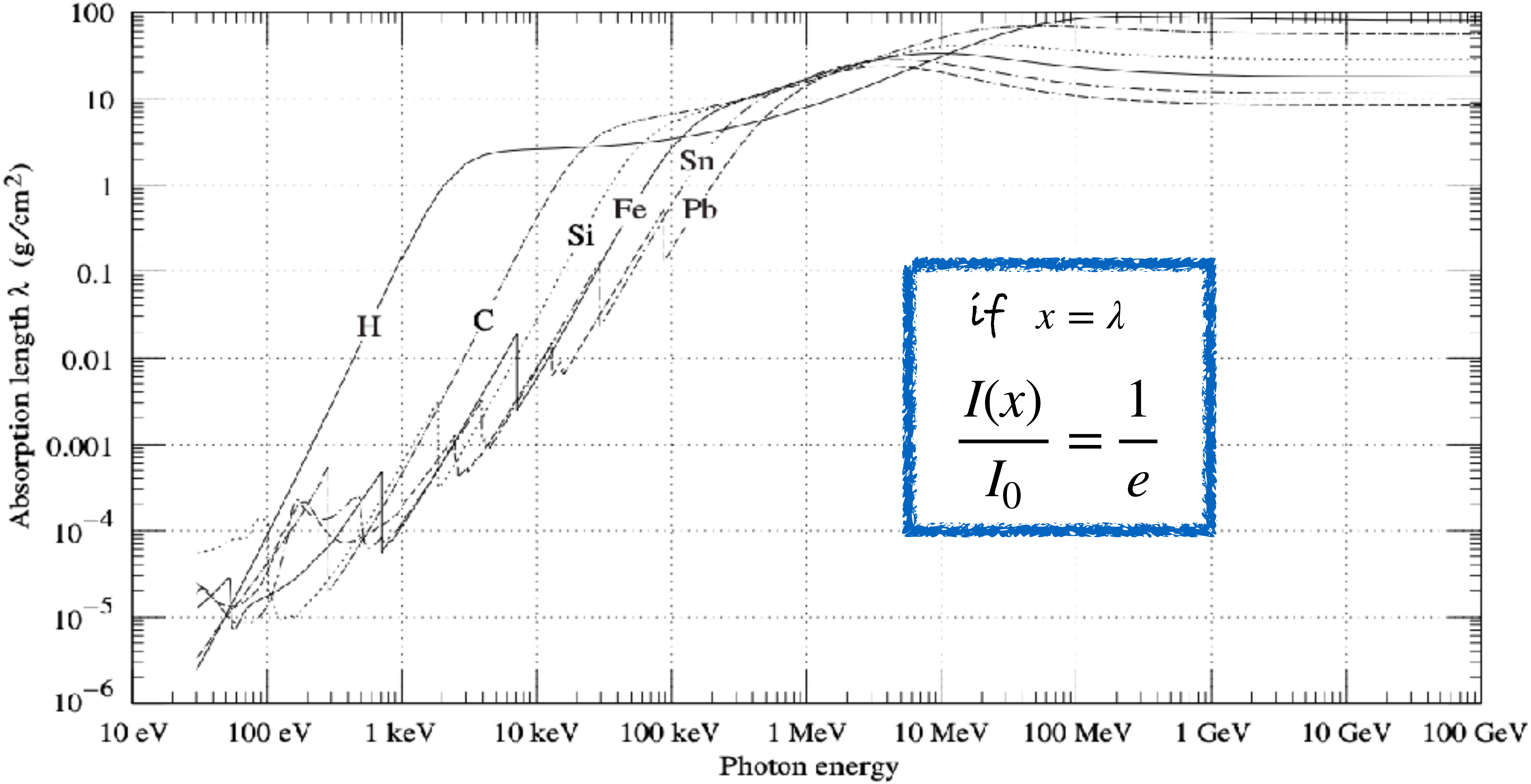
➔ Beer-Lambert law:

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

with $\boxed{\lambda = 1/\mu = 1/n\sigma}$ [mean free path]

Mean Free path

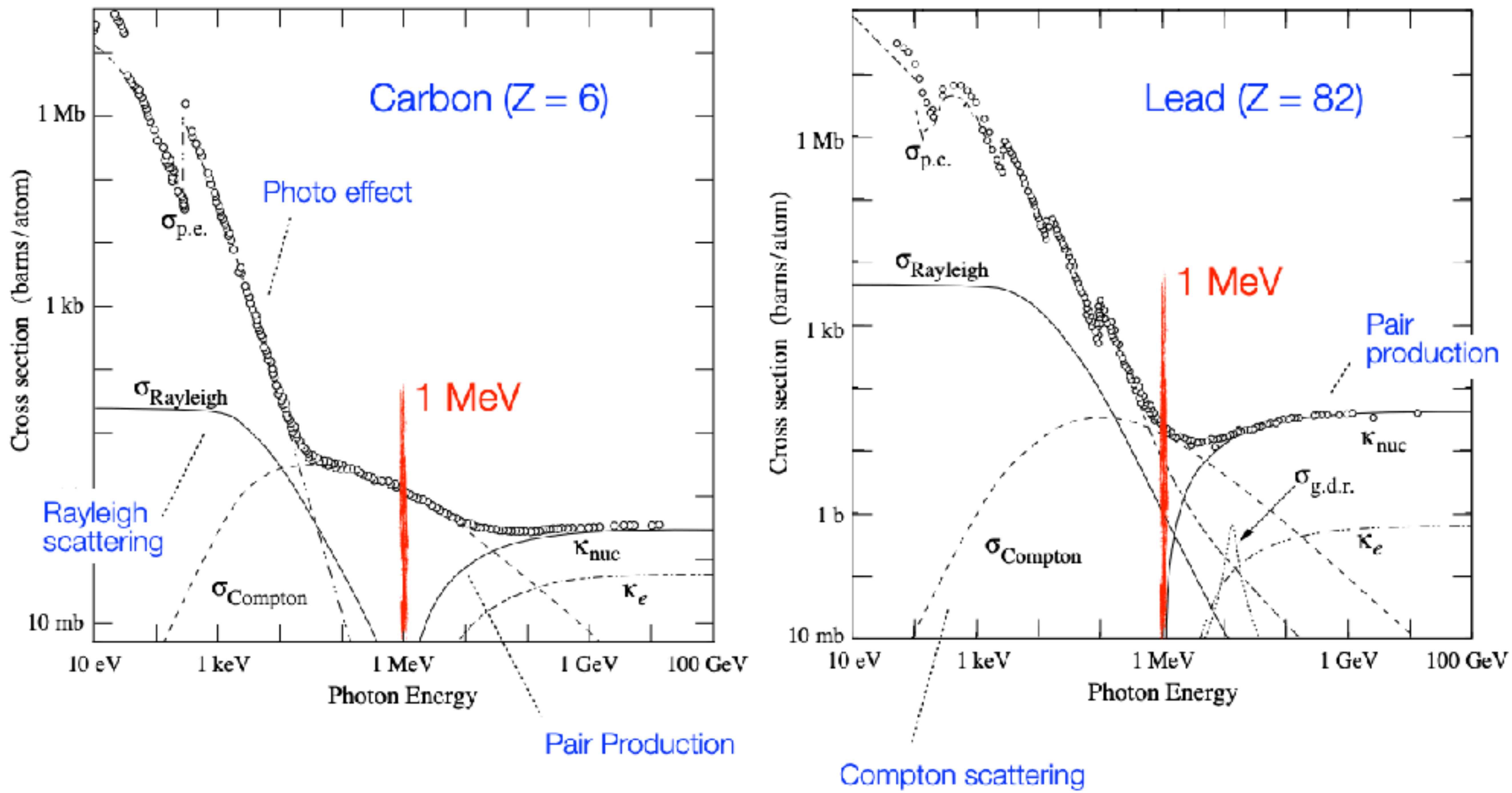
from PDG



if $x = \lambda$

$$\boxed{\frac{I(x)}{I_0} = \frac{1}{e}}$$

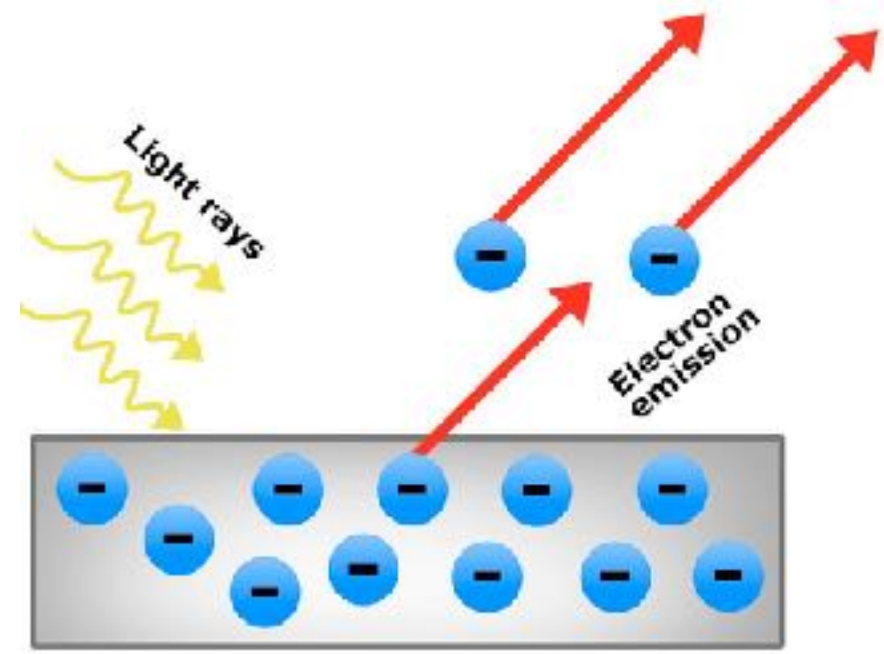
Photon Total Cross Sections



Photoelectric Effect

Einstein win nobel for this

* The photon is absorbed by the atom, an electron is emitted (ionization)



* Photon energy > binding energy (~20eV)
    * If not is Auger effect
* Cross section:

$$\sigma_{photo} = 4\alpha^4 \sqrt{2} Z^5 \frac{8\pi r_e^2}{3} \left(\frac{m_e c^2}{h\nu} \right)^{7/2}$$

$\propto E^{7/2}$

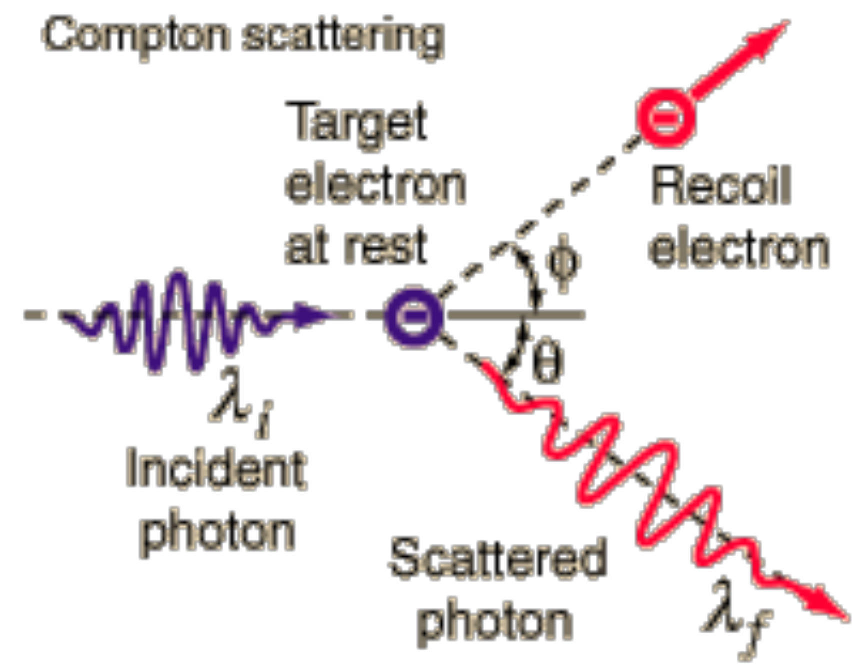
$\propto Z^4$ or Z^5

Compton

* X-rays interact directly with the atomic electrons

* Higher energy than photoelectric photons

* $\lambda_i \cong 0{,}02$ nm

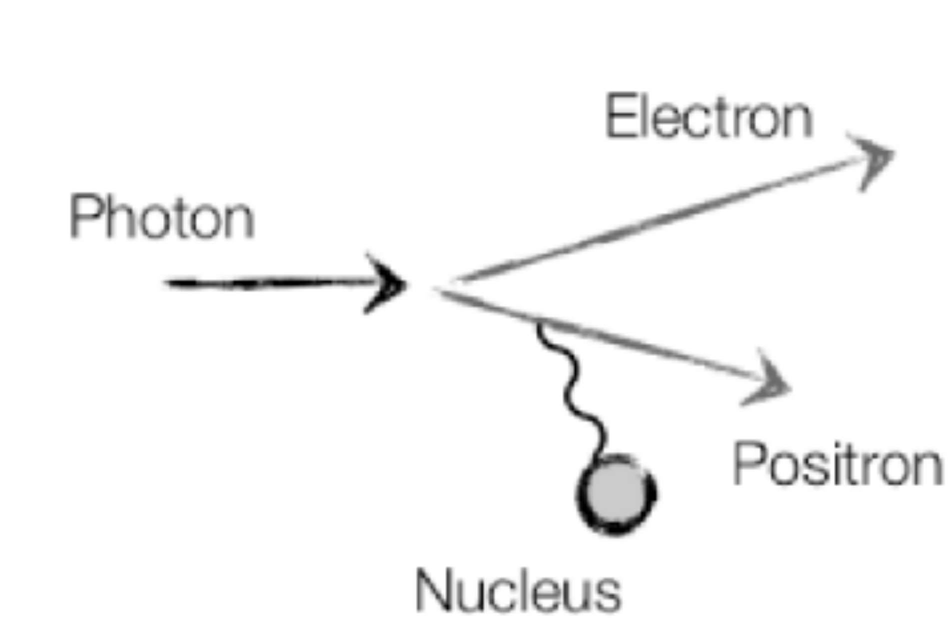


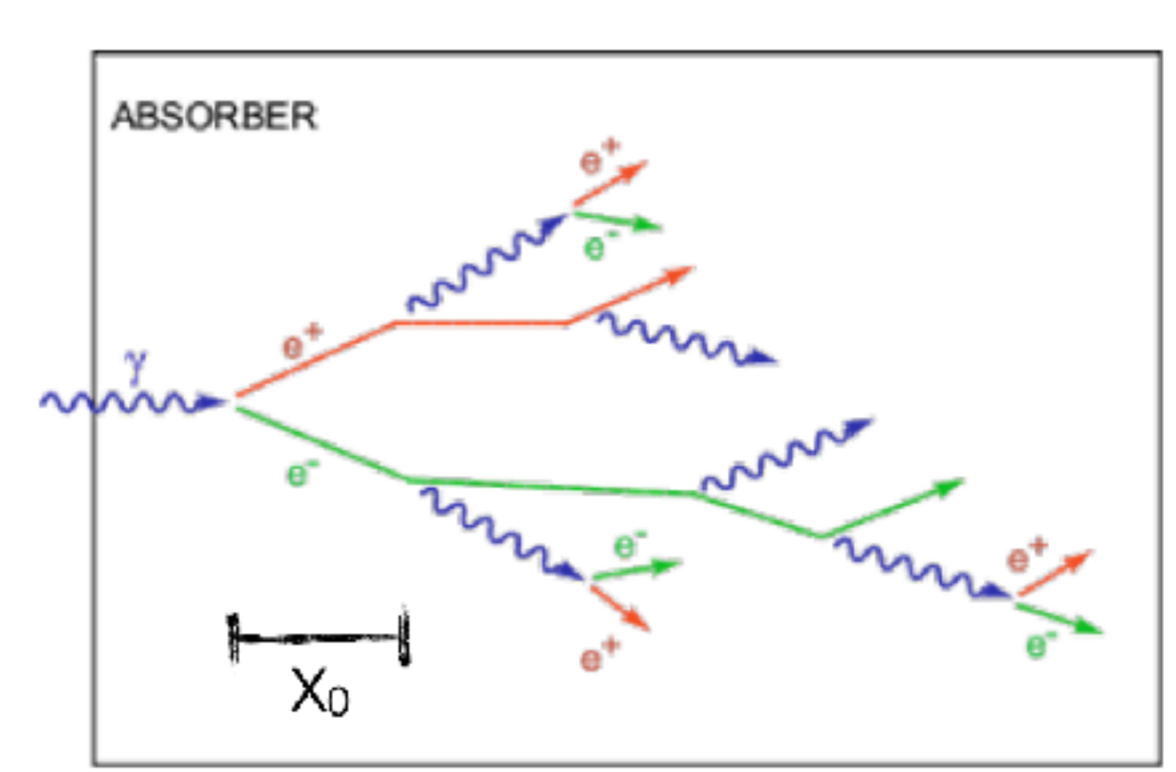
$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_e c}(1-\cos\theta)$$

Photon Pair Production

Cross Section:
[for $E_\gamma \gg m_e c^2$]

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln \frac{183}{Z^{\frac{1}{3}}}\right)$$





$E_{th} = 2m_e = 1{,}022$ KeV

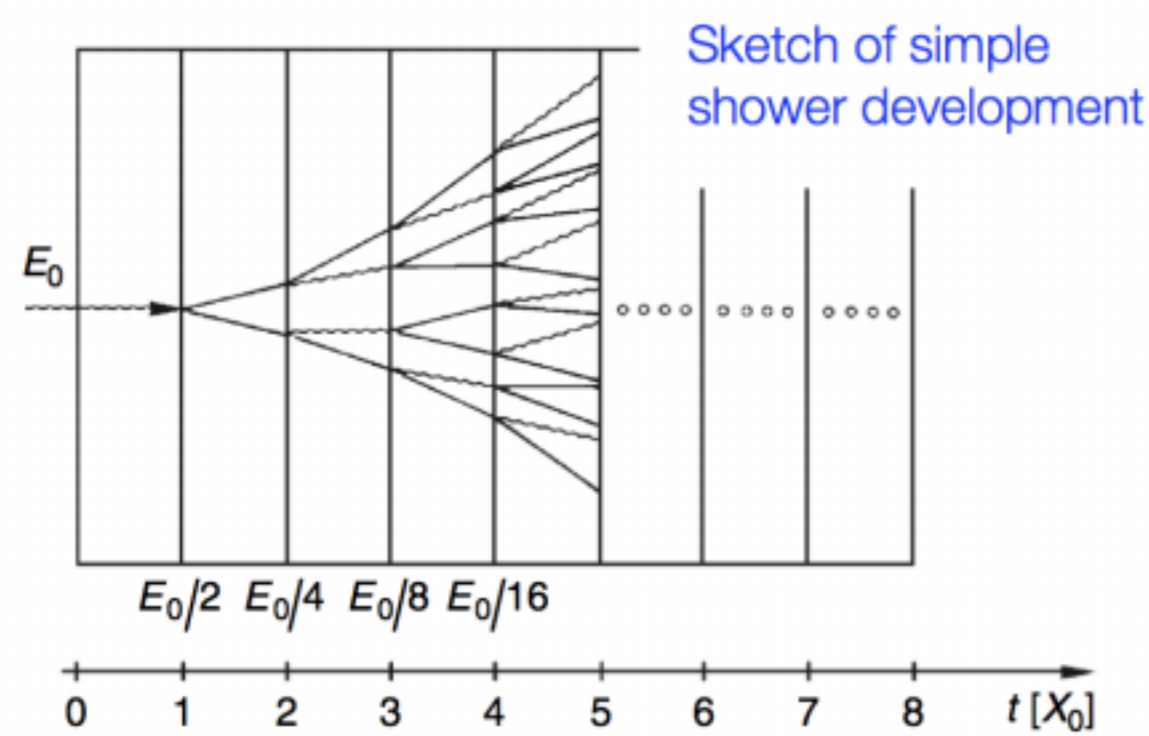
λ = mean free path

$$\lambda = \frac{9}{7} X_0$$

X_0 = radiation length = mean distance over which an <u>electron</u> loses all but 1/e of its energy.

Longitudinal Shower Profile

* After each interaction the particle energy halves
* Shower stops when the energy equals E_{th}



Number of shower particles after depth t:

$$N(t) = 2^t$$

Energy per particle after depth t:

$$E = \frac{E_0}{N(t)} = E_0 \cdot 2^{-t}$$

$$\rightarrow \quad t = \log_2(E_0/E)$$

Total number of shower particles with energy E_1:

$$N(E_0, E_1) = 2^{t_1} = 2^{\log_2(E_0/E_1)} = \frac{E_0}{E_1}$$

Number of shower particles at shower maximum:

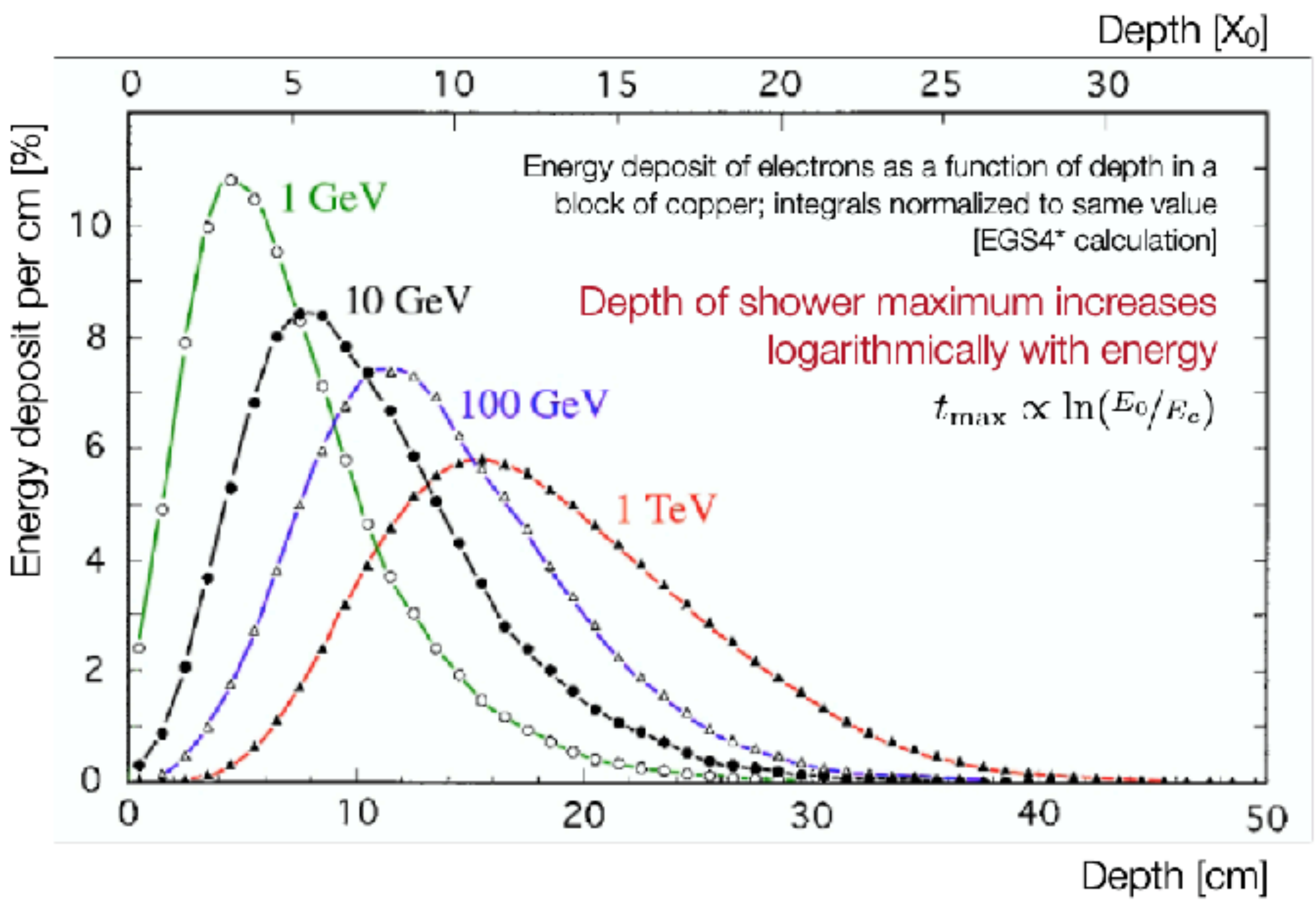
$$N(E_0, E_c) = N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_c}$$

$$\propto E_0$$

Shower maximum at:

$$t_{\max} \propto \ln(E_0/E_c)$$

Longitudinal Shower Profile



Longitudinal development scales with the radiation length

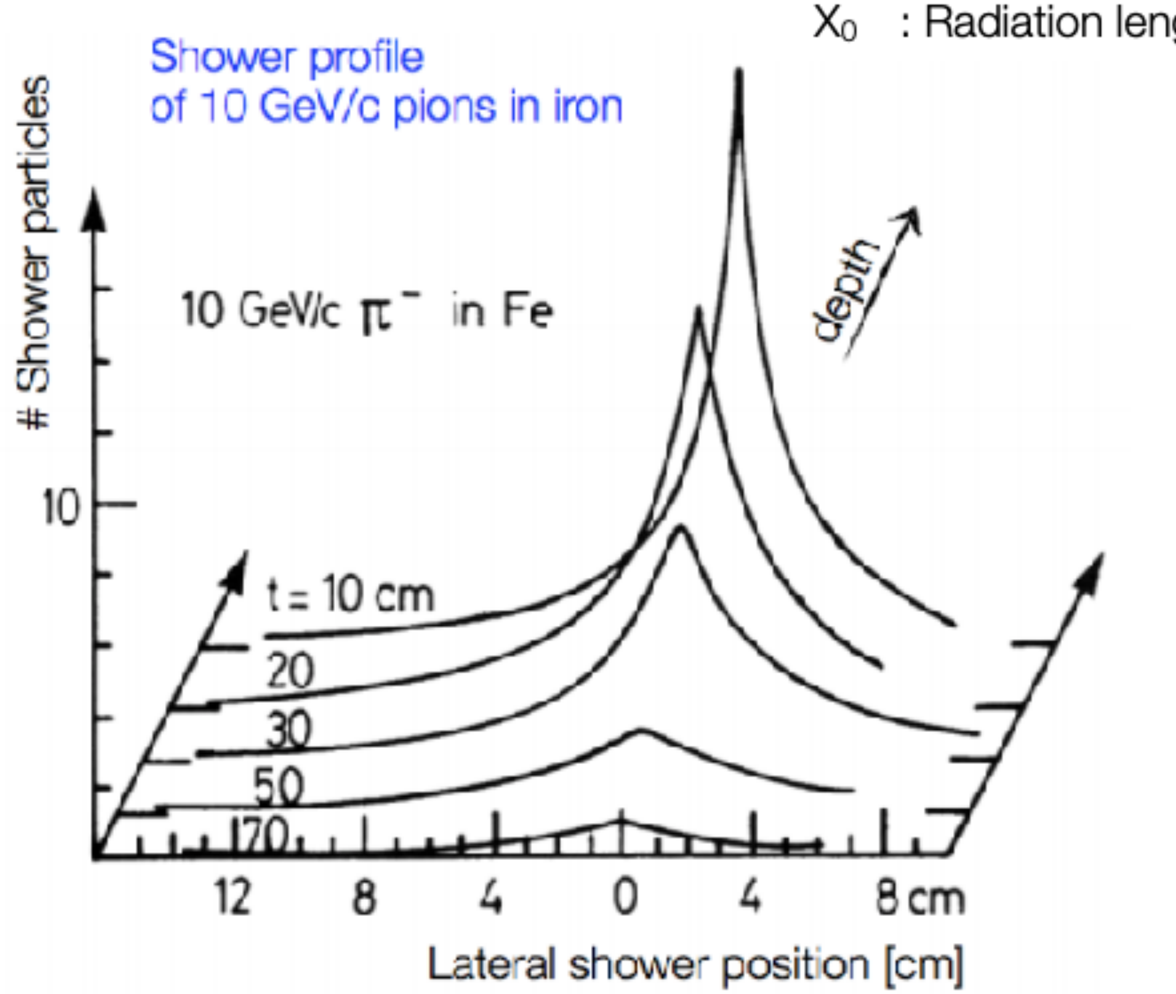
Electrons eventually fall beneath critical energy and then lose further energy through dissipation and ionization

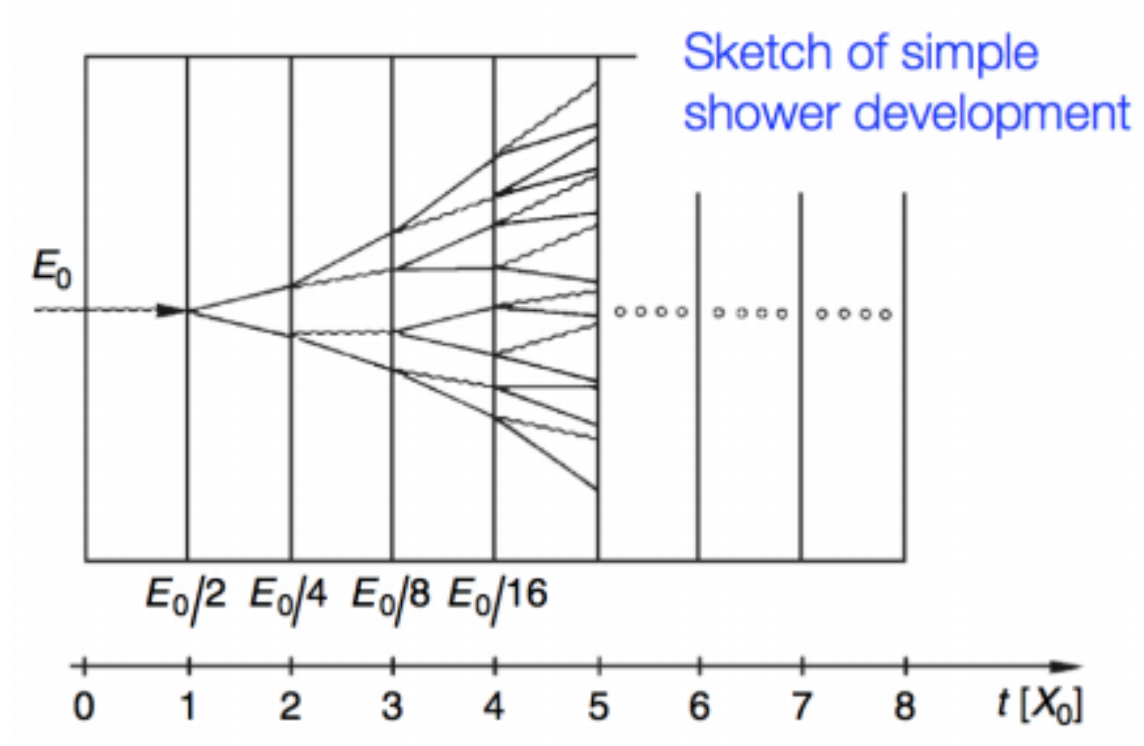
Transverse Shower Profile

Transverse size of EM shower given by radiation length via Molière radius

$$R_M = \frac{21\ \text{MeV}}{E_c} X_0$$

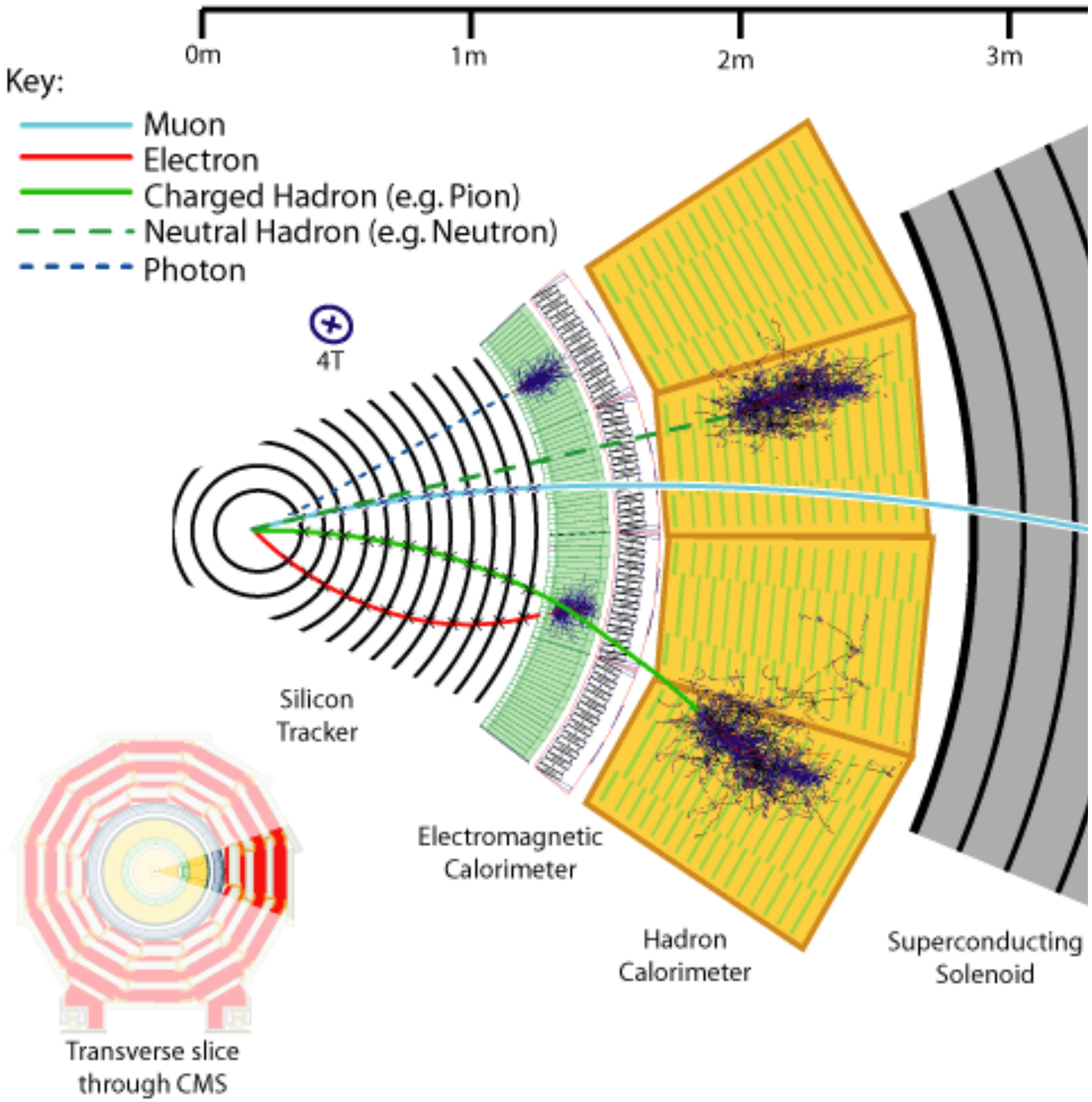
R_M : Moliere radius
E_c : Critical Energy [Rossi]
X_0 : Radiation length





Transverse development scales with the radiation length

Electromagnetic Cascades



E.M. Calorimeters

Photon (and Electron) Detection

N.B.: it interacts with all other charged particles anyway

E.M. Calorimeters

* In high energy physics we are interested at high energies ($E_\gamma >> MeV$)

* Photons interacts mostly by Pair Production

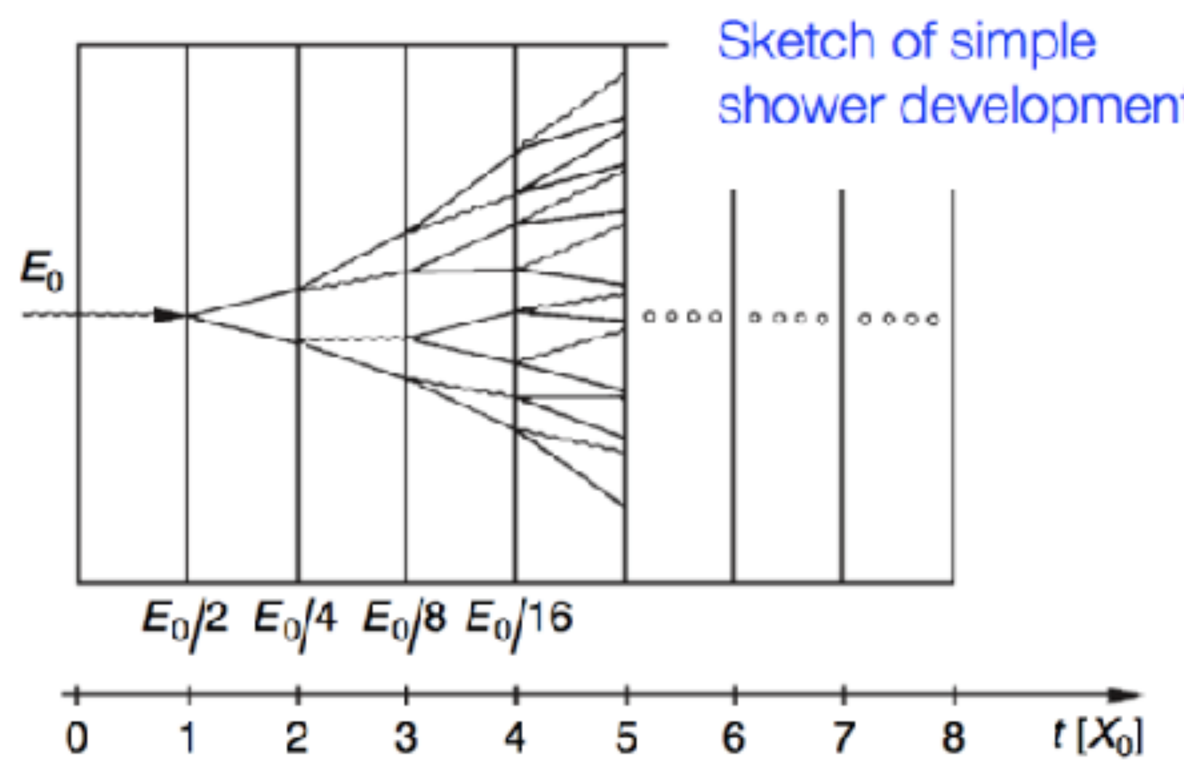
* We are interested in revealing showers

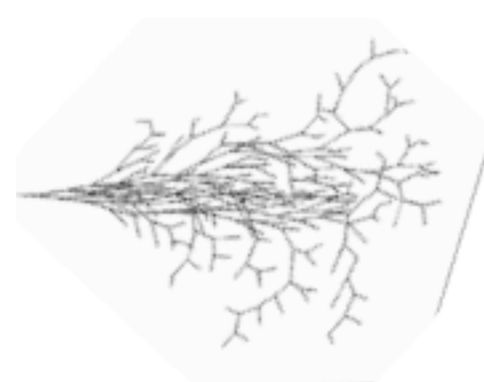
E.M. Calorimeters

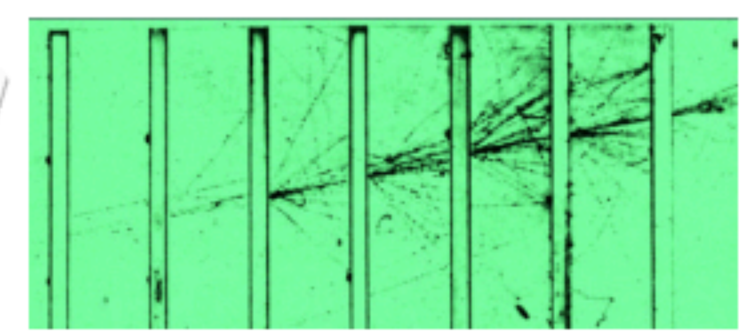
* In high energy physics we are interested at high energies ($E_\gamma >> MeV$)
* Photons interacts mostly by Pair Production
* We are interested in revealing showers

E.M. Calorimeters

* Calorimeters look at particle showers
* Shower is a complex object formed by multiple particles
* Study the shower property to understand the characteristic of the initial particle (e or γ)
* Strategy: look at the energy lost by electrons in the shower by ionisation
* Electron sensitive detector needed







E.M. Calorimeters

* Longitudinal depth used to evaluate the particle energy

$$t_{\max}[X_0] \sim \ln \frac{E_0}{E_c}$$

* So it must be longitudinally segmented!

* Transverse segmentation gives info on the particle position and direction (for charged particles trackers are better)

* The energy resolution (uncertainty) depends on the inverse of sqrt(number of steps t) for Poisson. But t proportional to the initial energy, so...

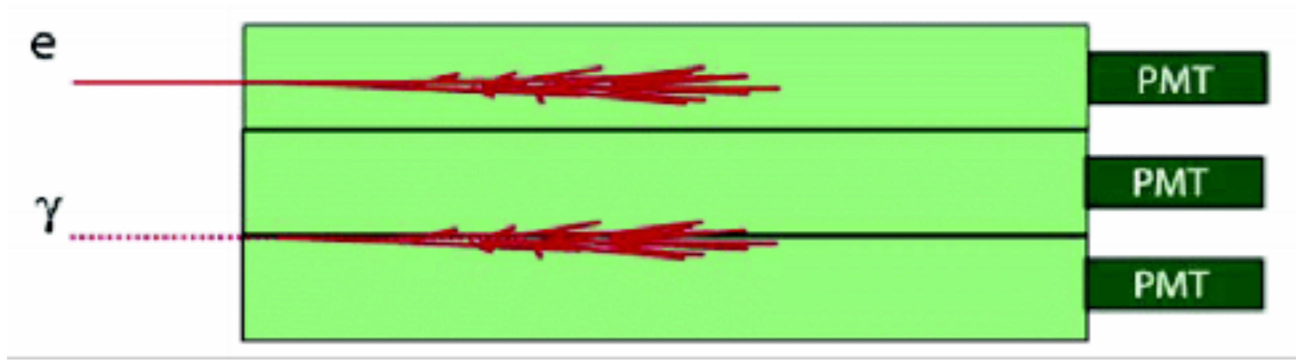
$$\frac{\sigma(E)}{E} = \frac{A}{\sqrt{E}}$$

* N.B. : to have the total energy the shower must be fully contained in the calorimeter

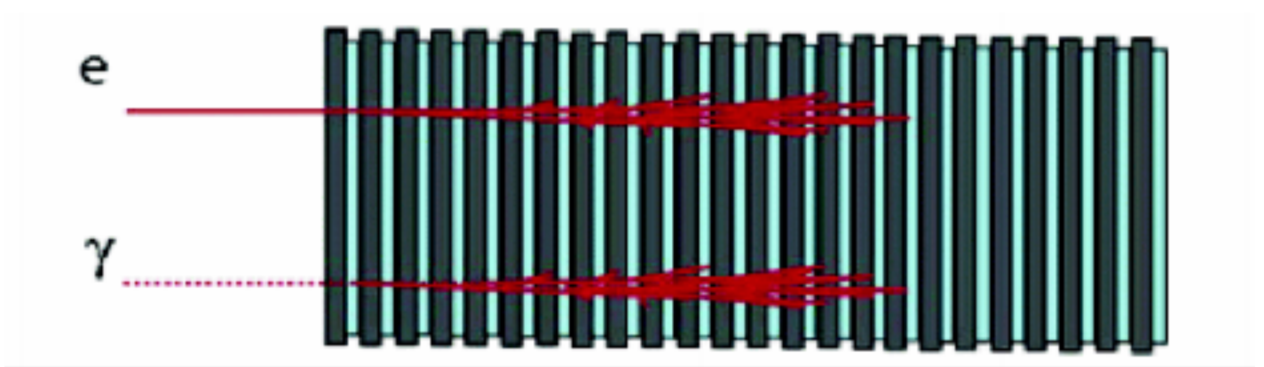
E.M. Calorimeters

- *initiate an em shower (high Z)*
- *collect shower energy (light) lost by ionization*

- **homogeneous:** *the sensitive detector is the same that causes the em shower.*
  - *based on crystal (BGO, NaI, Pb—glass), high density,*
  - *excellent resolution, expensive*



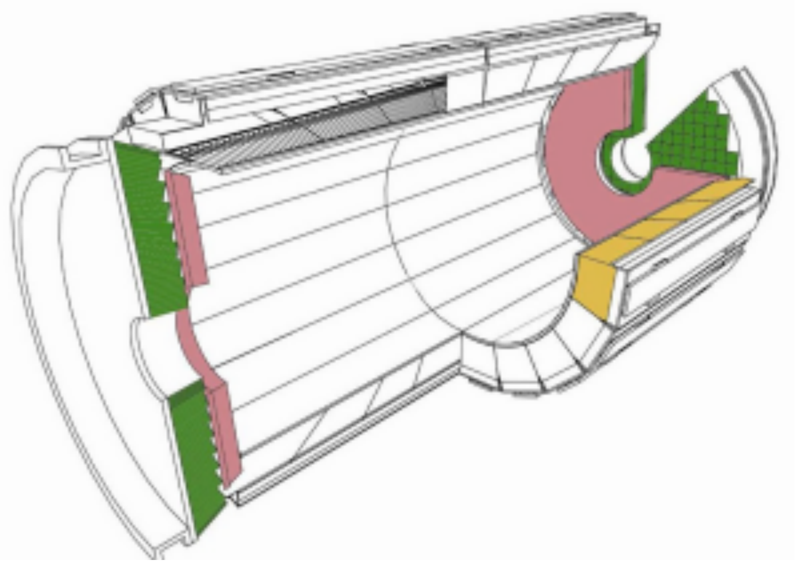
- **sampling:** *alternating layers of passive and sensitive material*
  - *gas, silicon (sensitive)*
  - *Passive dense material (Fe, Pb, W, ...),*
  - *poorer resolution, compact, cheap*

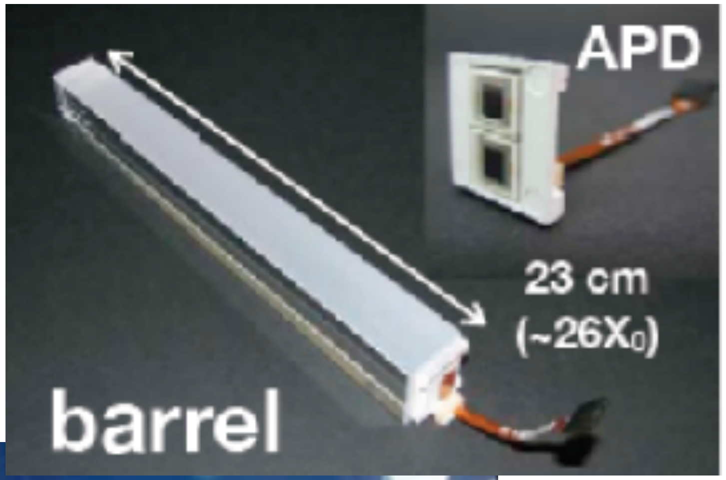


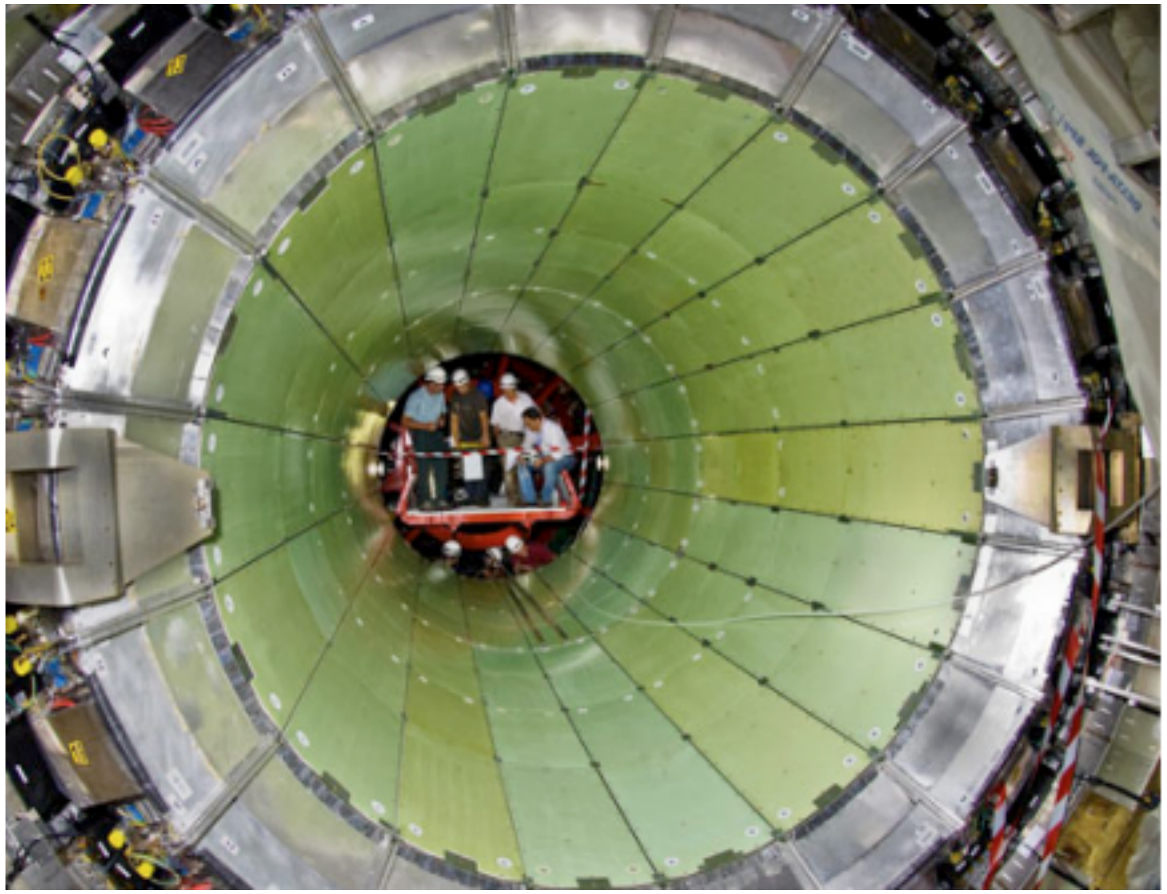
Examples of Homogeneous Calo

CMS ECal

- Scintillator: PbWO
- ~3x3x23 cm
- 70000 crystals

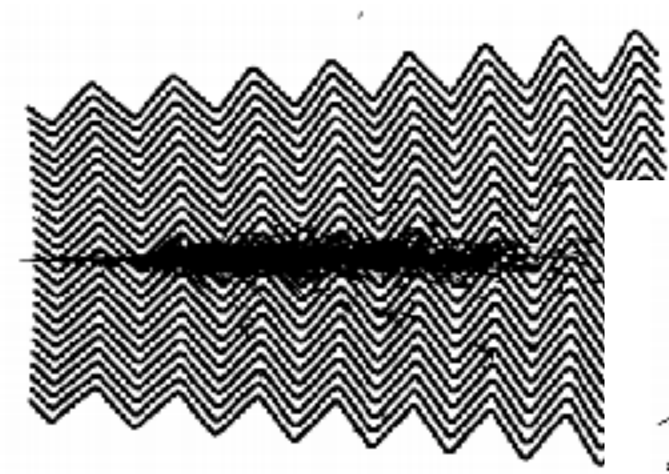


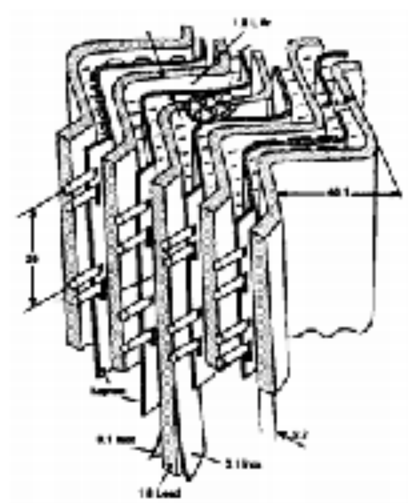


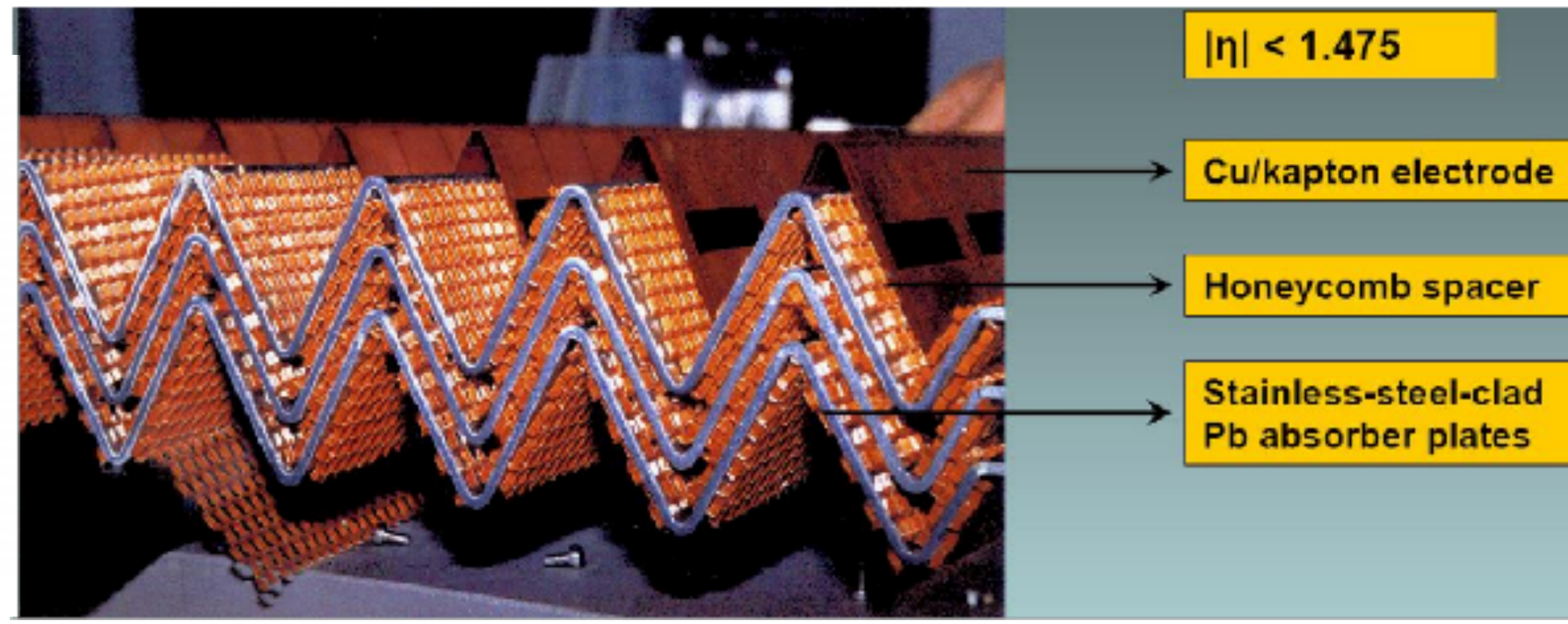


Examples of Sampling Calo

ATLAS LAr







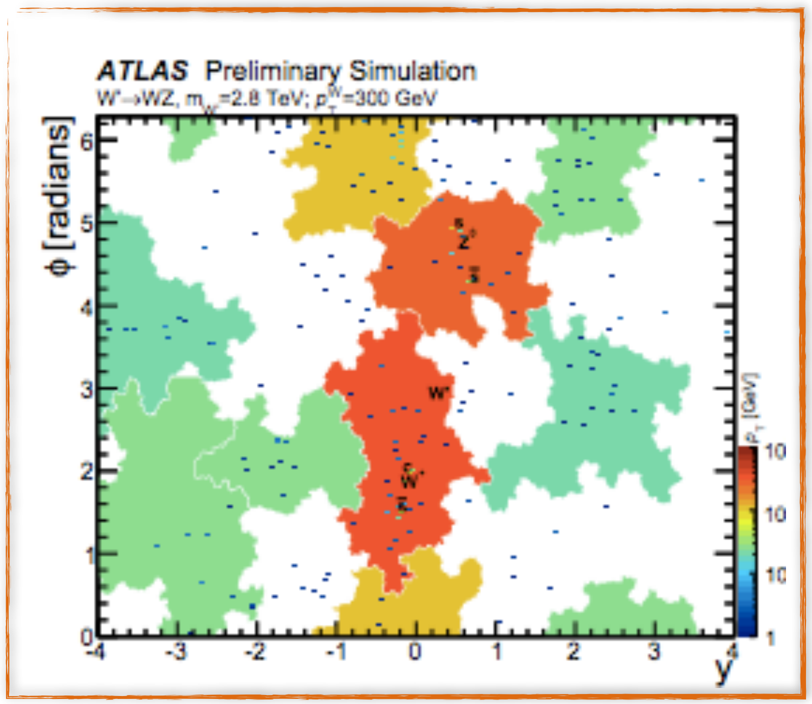
* Corrugated stainless steel clad Pb absorber sheets,1—2 mm thick
* Immersed in liquid argon (90K) (similar principle of gas detectors, but liquid)
* Collect ionisation electrons with an electric field across 2.1 mm liquid Argon drift gap

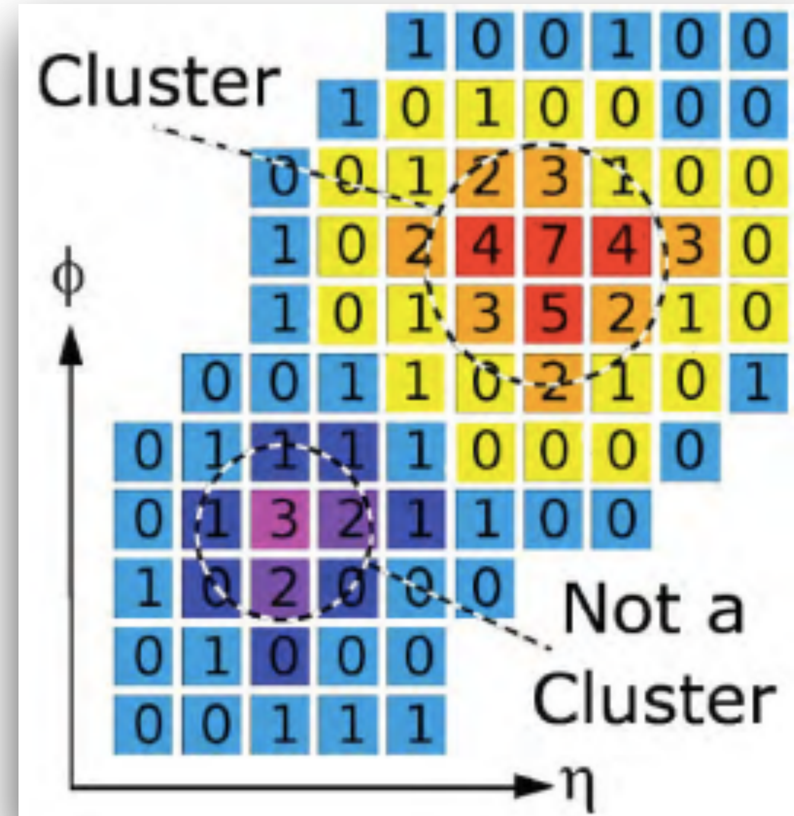
Cluster

Units in
$|E|/\sigma_{noise}$

$$\rho_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right)\frac{(\Delta R_{ij})^2}{R^2}$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2$$

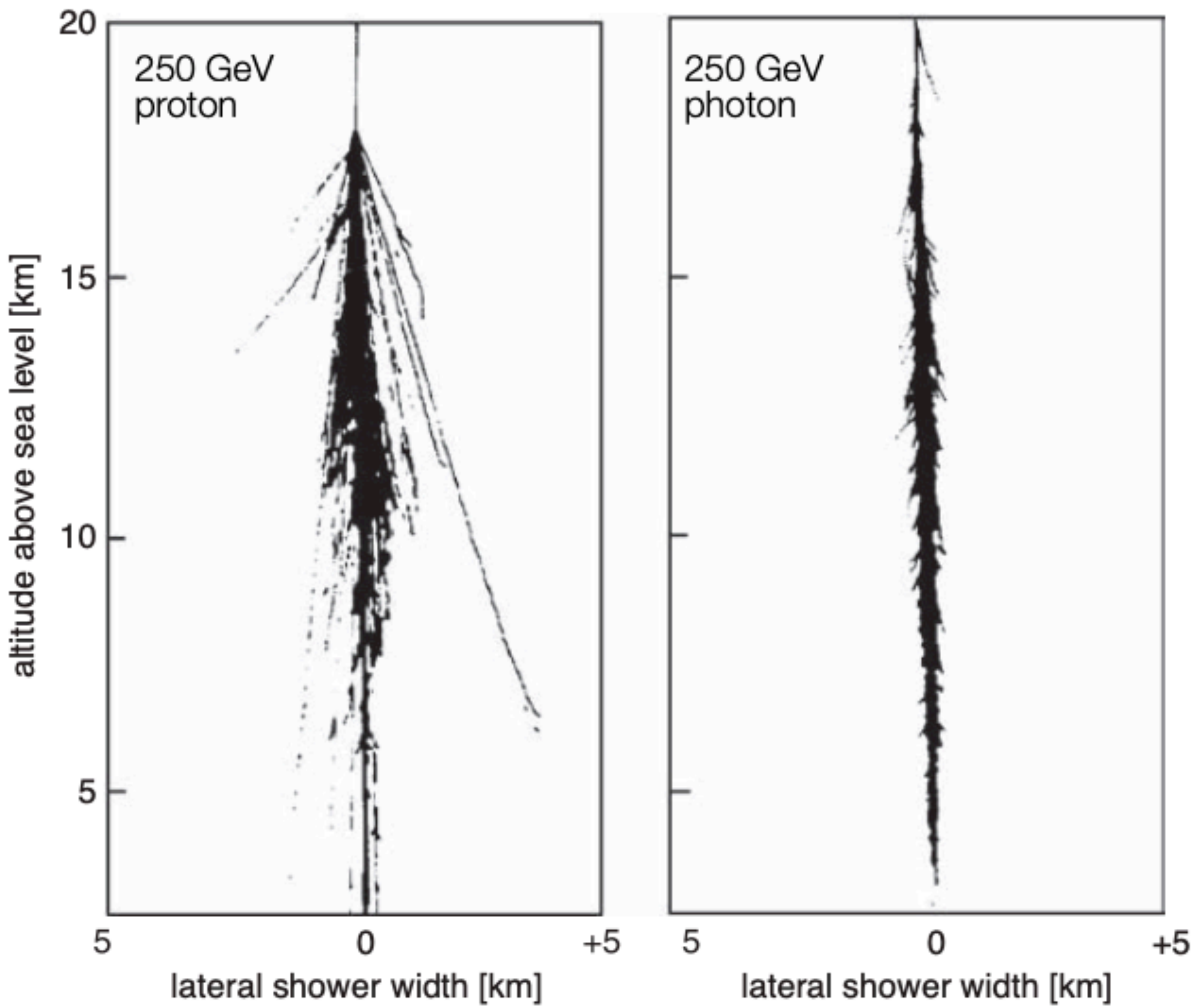




- Averaged weight on distance and energy deposition in each cell

- Similar to the center of mass definition

Hadron VS EM



250 GeV
proton
250 GeV
photon
20
15
10
5
altitude above sea level [km]
5
0
+5
lateral shower width [km]
5
0
+5
lateral shower width [km]

Muon Energy Loss (extra)

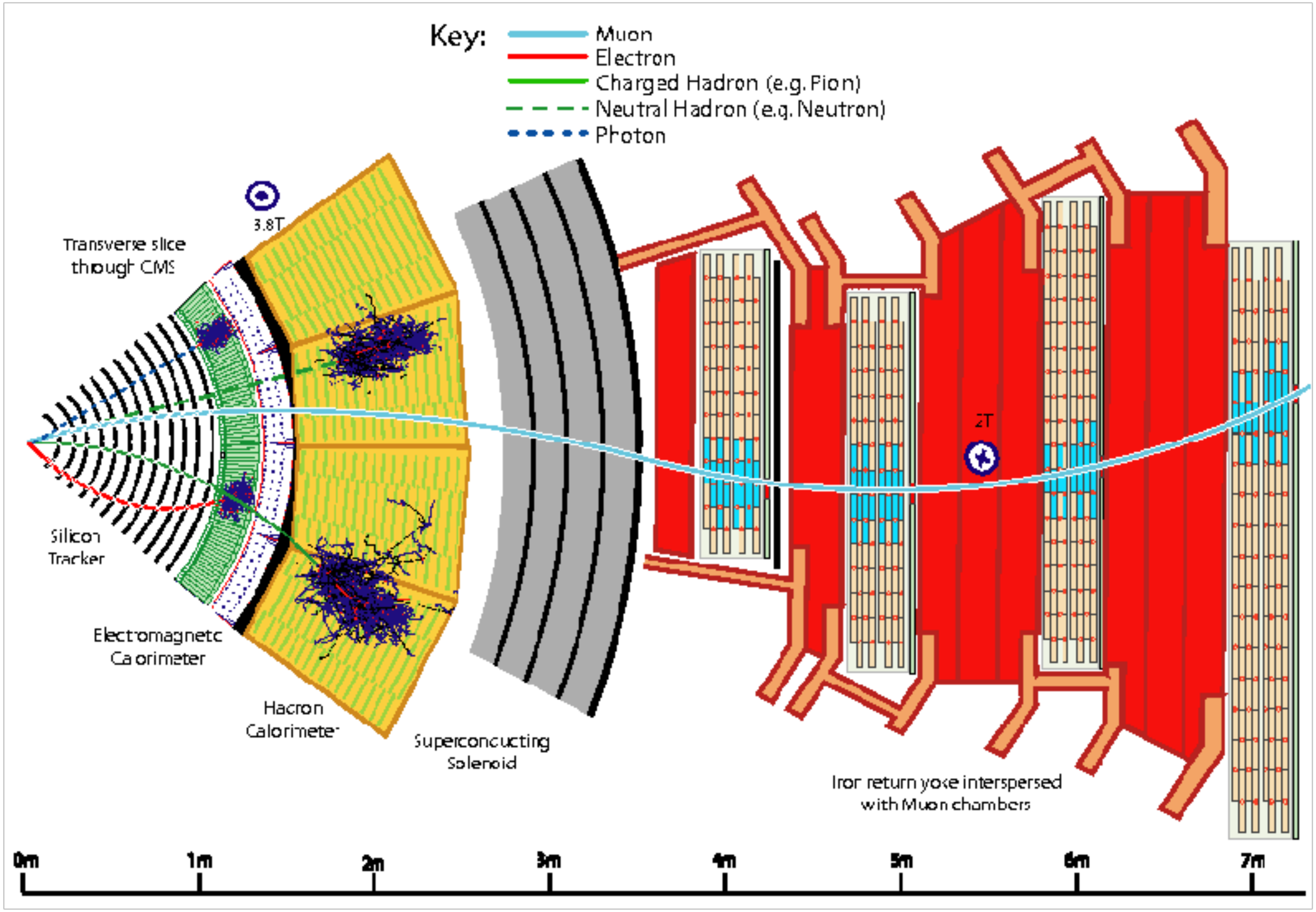
Muon Energy Loss

* Less interacting charged particles.

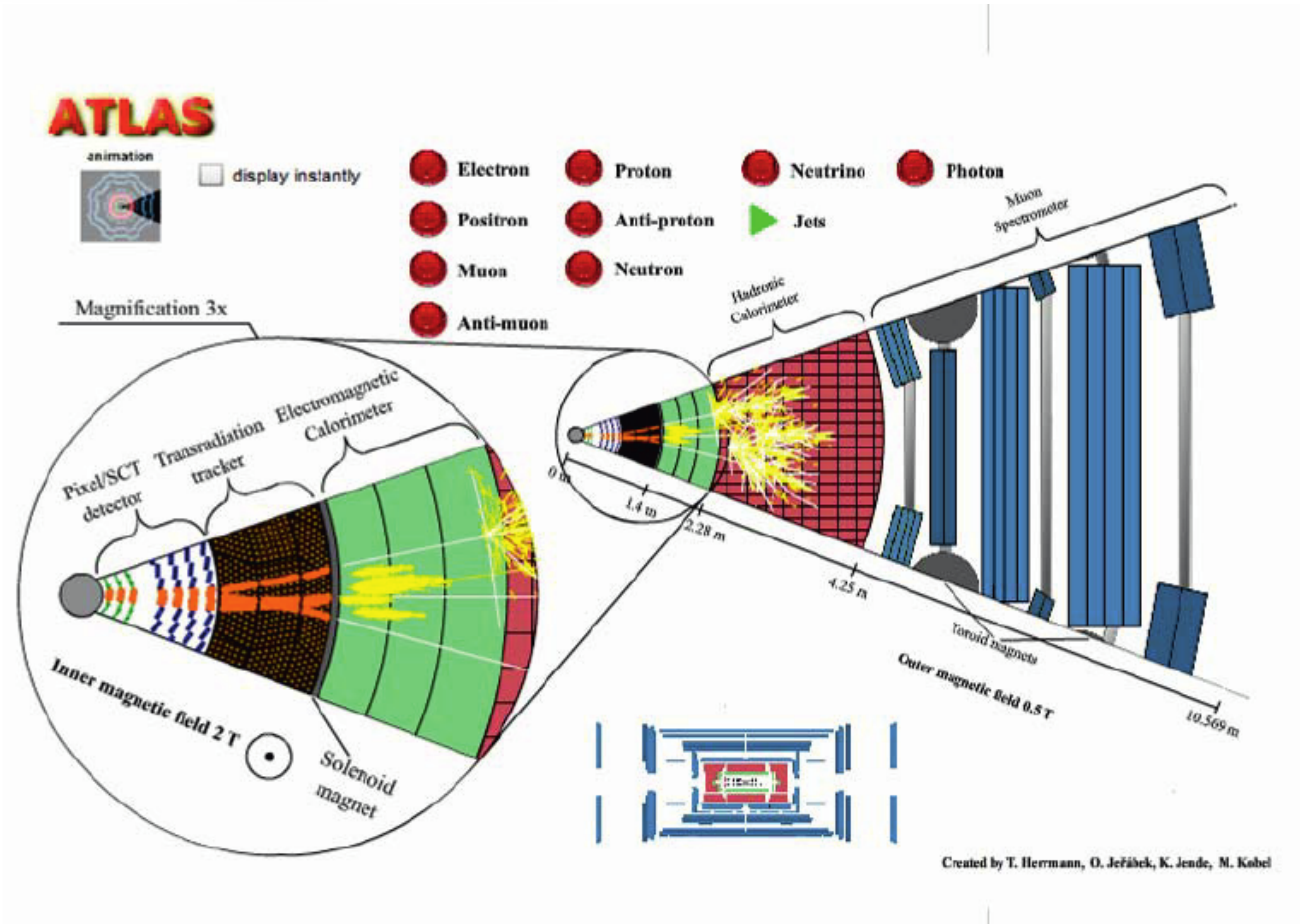
* Lose few energy in the detector —> long range

* Outer detectors to identify them. Match with other detectors to have more precise information.

CMS


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
3.8T
Transverse slice through CMS
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

ATLAS


ATLAS
animation
display instantly
Electron
Proton
Neutrino
Photon
Positron
Anti-proton
Jets
Muon
Neutron
Anti-muon
Magnification 3x
Muon Spectrometer
Hadronic Calorimeter
Pixel/SCT detector
Transradiation tracker
Electromagnetic Calorimeter
Inner magnetic field 2 T
Solenoid magnet
0 m
1.4 m
2.28 m
4.25 m
Toroid magnets
Outer magnetic field 0.5 T
10.569 m
Created by T. Herrmann, O. Jeřábek, K. Jende, M. Kobel