Detectors Physics Lecture I: Particle Interactions with Matter

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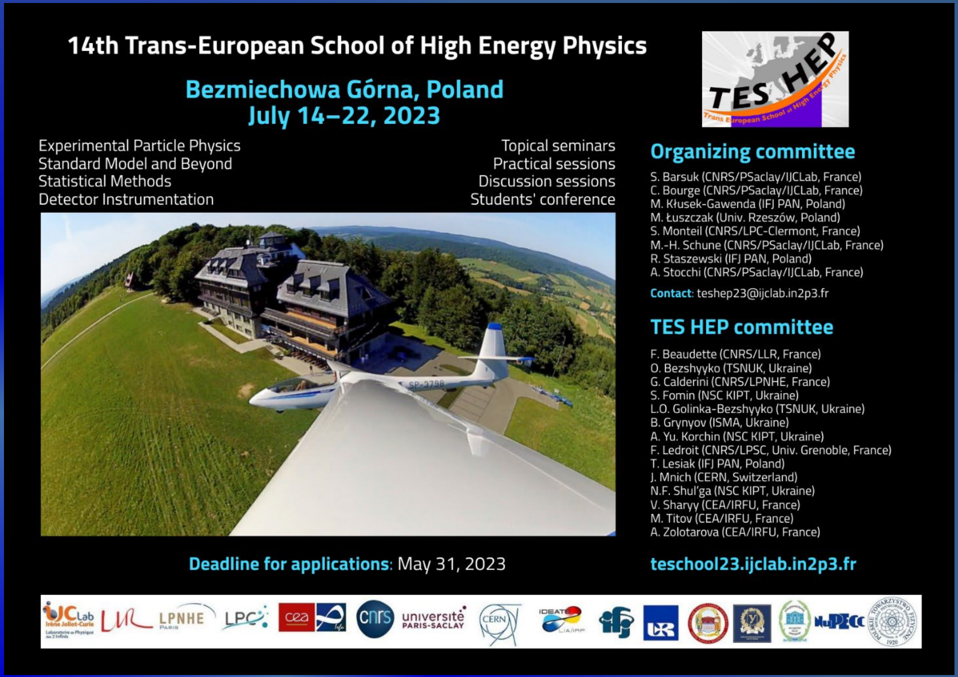

14th Trans-European School of High Energy Physics

Bezmiechowa Górna, Poland
July 14–22, 2023

Experimental Particle Physics
Standard Model and Beyond
Statistical Methods
Detector Instrumentation

Topical seminars
Practical sessions
Discussion sessions
Students' conference

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Deadline for applications: May 31, 2023

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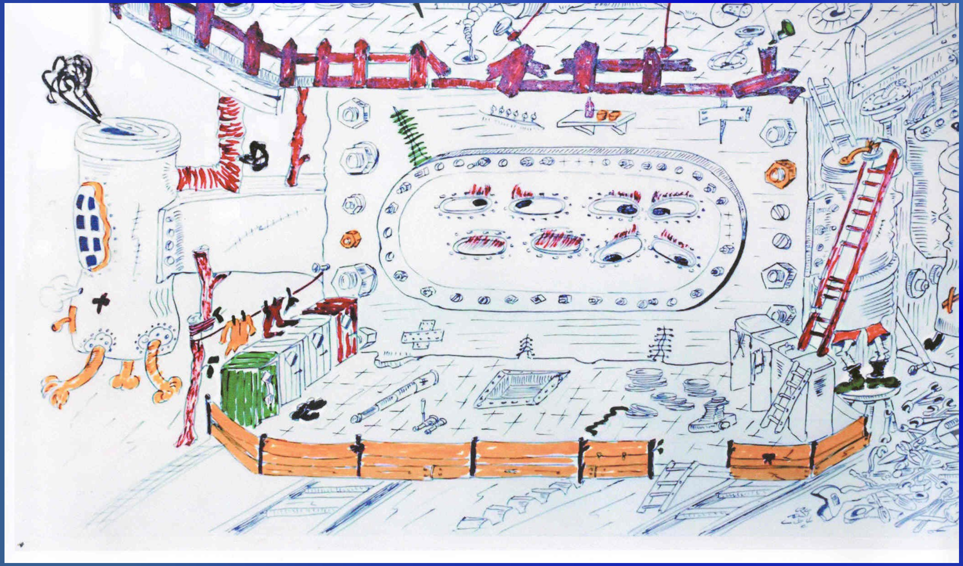
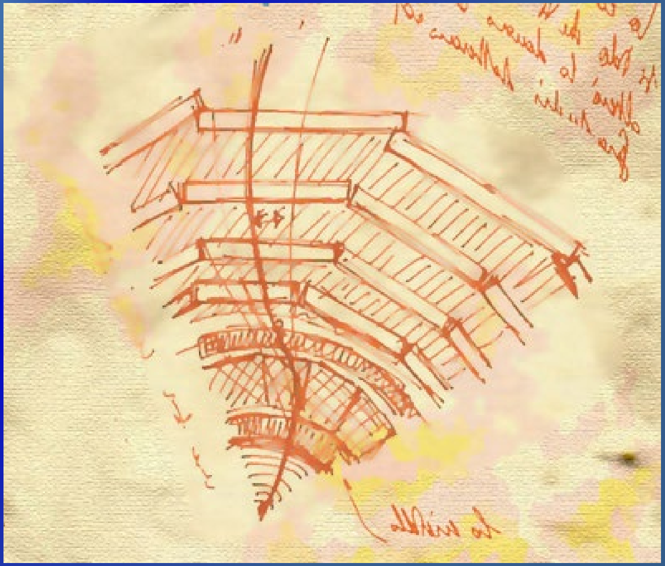
Artist's View of a Bubble chamber by a CERN physicist





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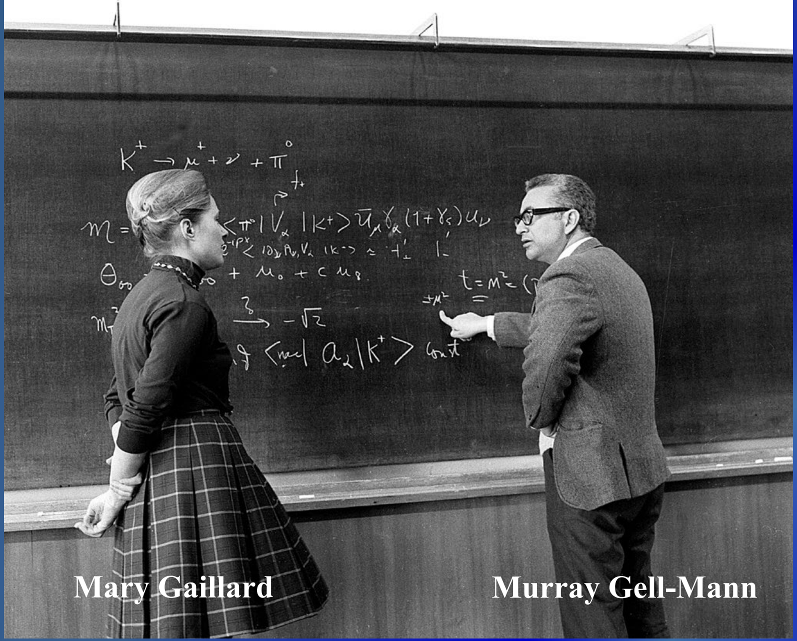
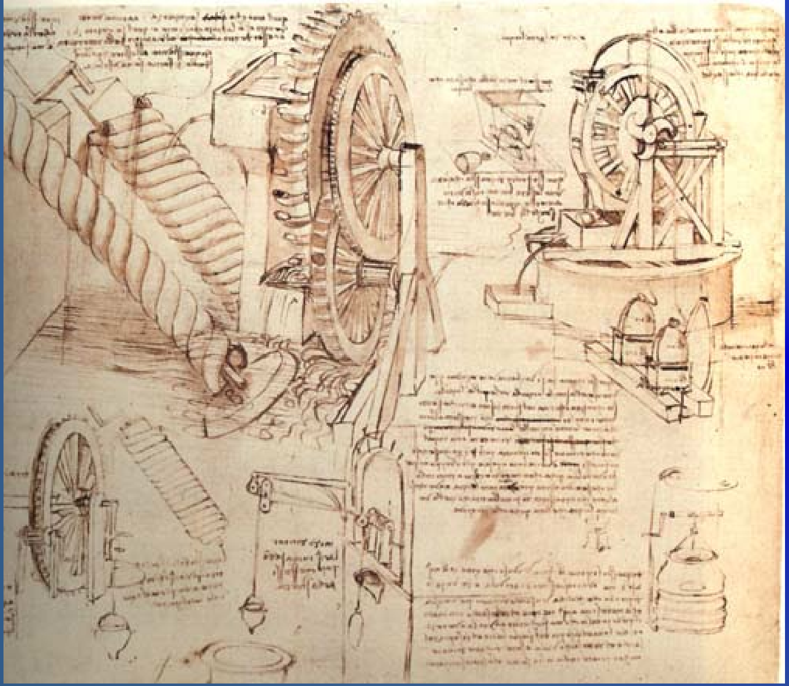
To make a collider experiment, one needs:



A theory:

and a cafeteria

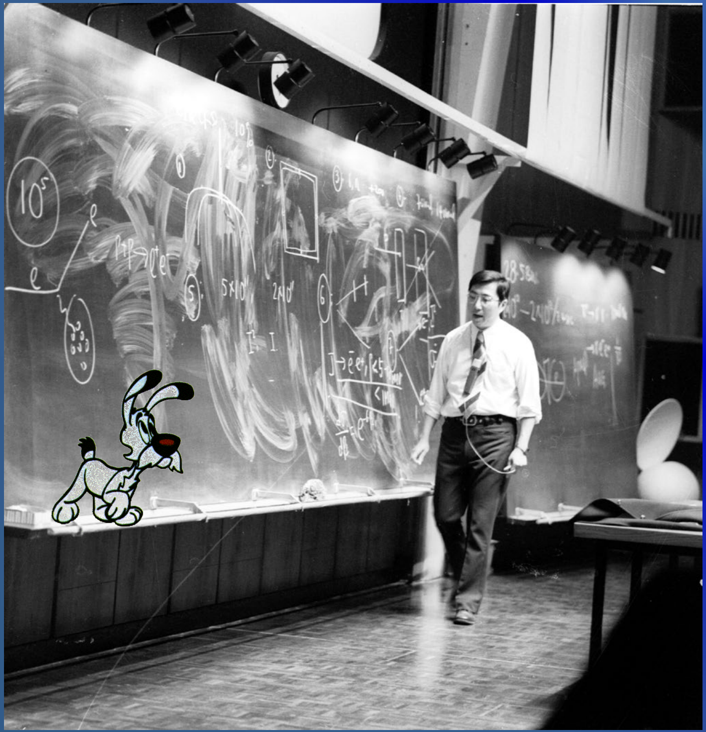


Clear and easy understandable drawings

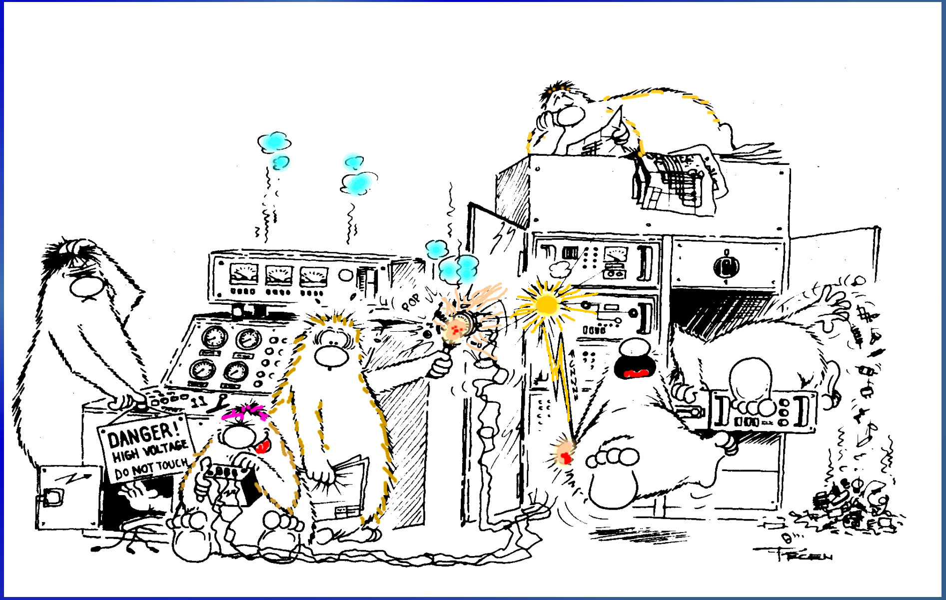
and a tunnel for the accelerator and magnets and stuff

Easy access to the experiment

Physicists to operate detector/analyze data



and a Nobel prize



We will just concentrate on Particle Detectors

The History of Instrumentation is VERY Entertaining

✓ A look at the history of instrumentation in particle physics

→ complementary view on the history of particle physics, which is traditionally told from a theoretical point of view

✓ The importance and recognition of inventions in the field of instrumentation is proven by the fact that

→ several Nobel Prices in physics were awarded mainly or exclusively for the development of detection technologies

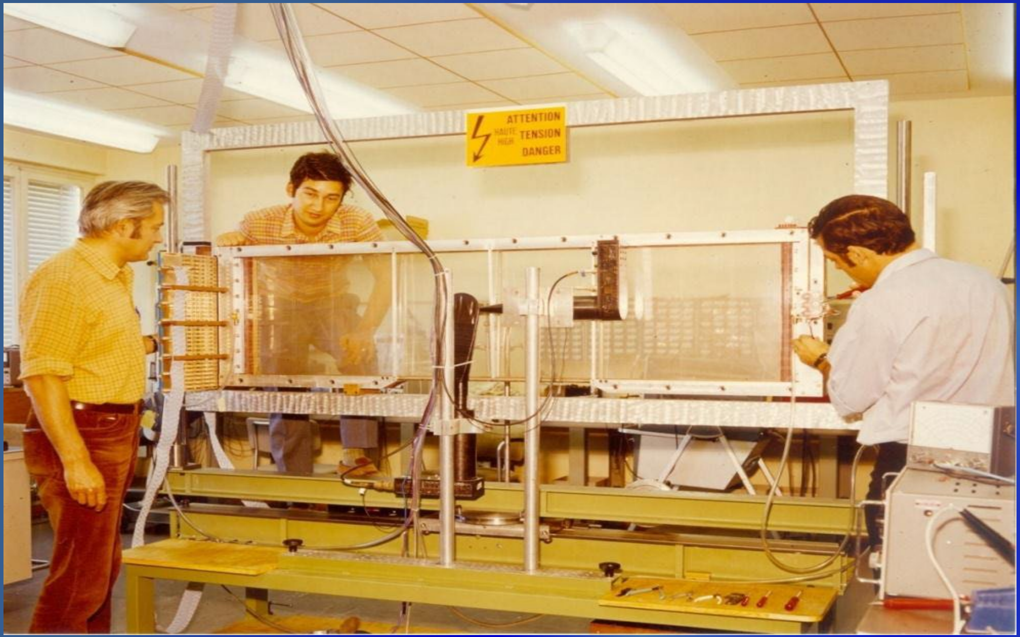
Nobel Prizes in instrumentation (“tracking concepts”):

❖ 1927: C.T.R. Wilson, Cloud Chamber

❖ 1960: Donald Glaser, Bubble Chamber

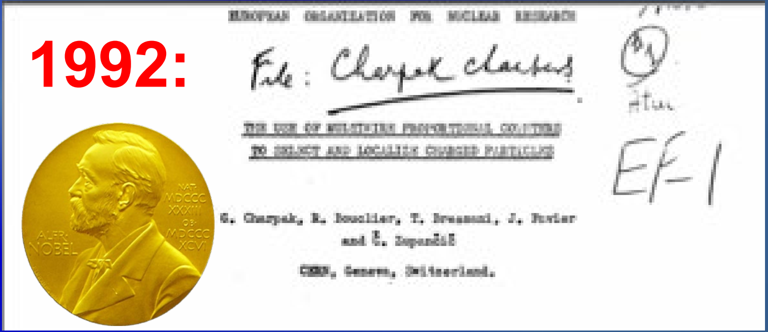
❖ 1992: Georges Charpak, Multi-Wire Proportional Chamber

1968: MWPC – Revolutionising the Way Particle Physics is Done



Detecting particles was a mainly a manual, tedious and labour intensive job – unsuited for rare particle decays

1968: George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and High Energy Physics - which passed from the manual to the electronic era.



1992:

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File : Charpak chambers

EF-1

THE USE OF MULTIWIRE PROPORTIONAL COUNTERS
TO SELECT AND LOCALIZE CHARGED PARTICLES

G. Charpak, R. Bouclier, T. Bressani, J. Favier
and Č. Zupančič

CERN, Geneva, Switzerland.

Electronic particle track detection is now standard in all particle detectors

Detector & Measurements: How Do We Do Physics Without Seeing?

The Goal: to see what others cannot see …

The bigger picture

Quarks. Gluons. Neutrinos. All those damn particles you can't see. That's what drove me to drink. But now I can see them!

Interactions of Particles and γ-Radiation with Matter

➔ If the particle is to pass through essentially undeviated, this interaction must be a soft electromagnetic one.

➔ *Otherwise, measure energy loss or total energy for total absorption detectors (Particle ID from gaseous detectors, Cherenkov detectors, Transition Radiation Detectors, Calorimeters, Energy measurement from Calorimetry)*

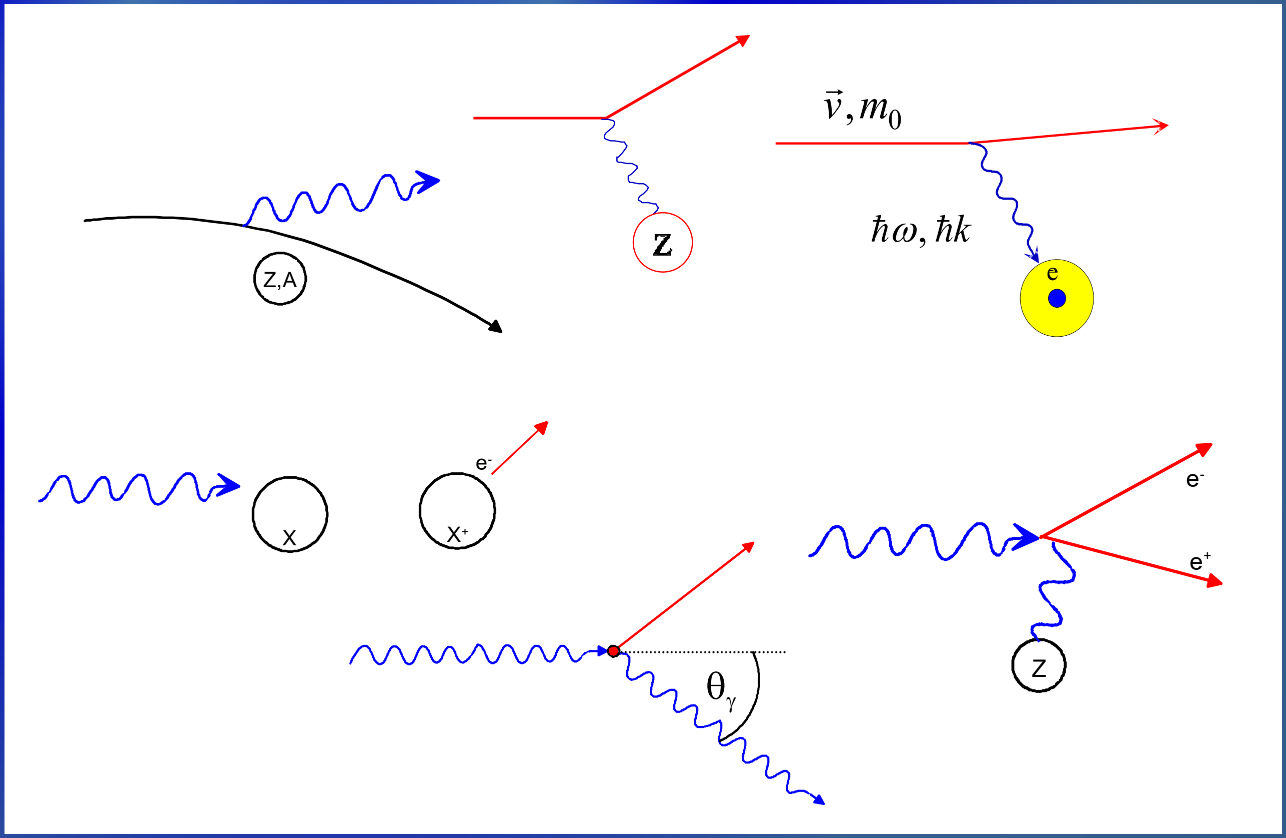
✓ ***Charged particles***
- **Ionization**
- **Photon Emission:**
  - **- Bremsstrahlung**
  - **- Čerenkov Radiation**
  - **- Transition Radiation**
  - **- Excitations (Scint.)**

✓ ***Detection of γ-rays***
- **Photo Effect**
- **Compton Scattering**
- **Pair Creation**

✓ ***Detection of neutrons***
  - **- Strong interaction**

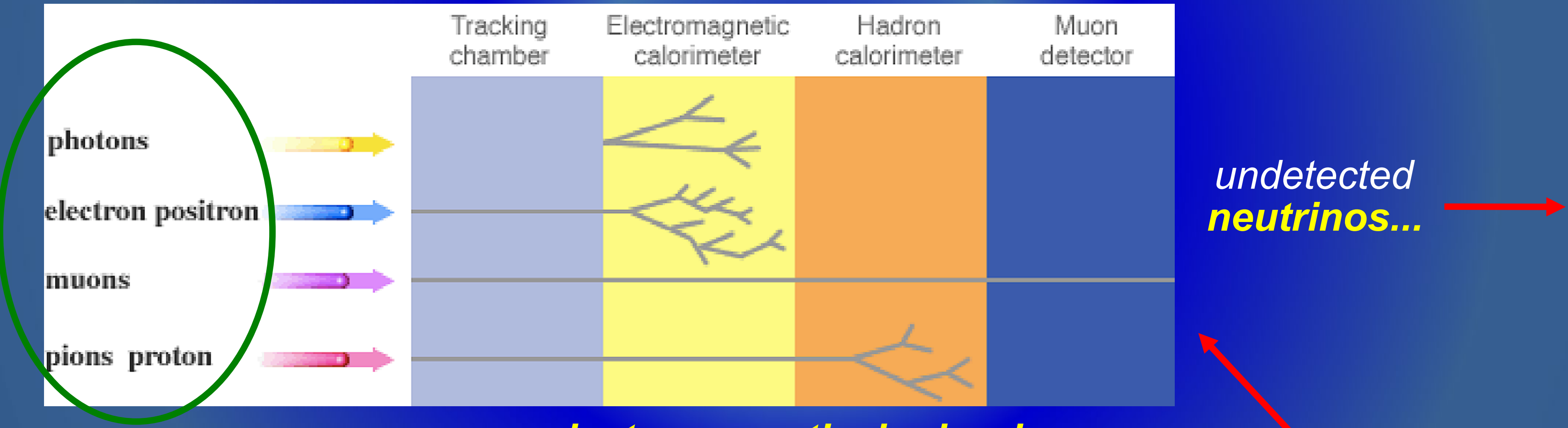
✓ ***Detection of neutrinos***

✓ **- Weak interaction**



Schematic View of a Particle Collider Detectors

- *There is not one type of detector which provides all measurements we need -> "Onion" concept -> different systems taking care of certain measurement*
- Detection of collision production within the detector volume
  - → resulting in signals due to electro-magnetic interaction
  - → exceptions: strong interactions in hadronic showers (hadron calorimeters)
  - → weak interactions at neutrino detection (not discussed here)



undetected ***neutrinos...***

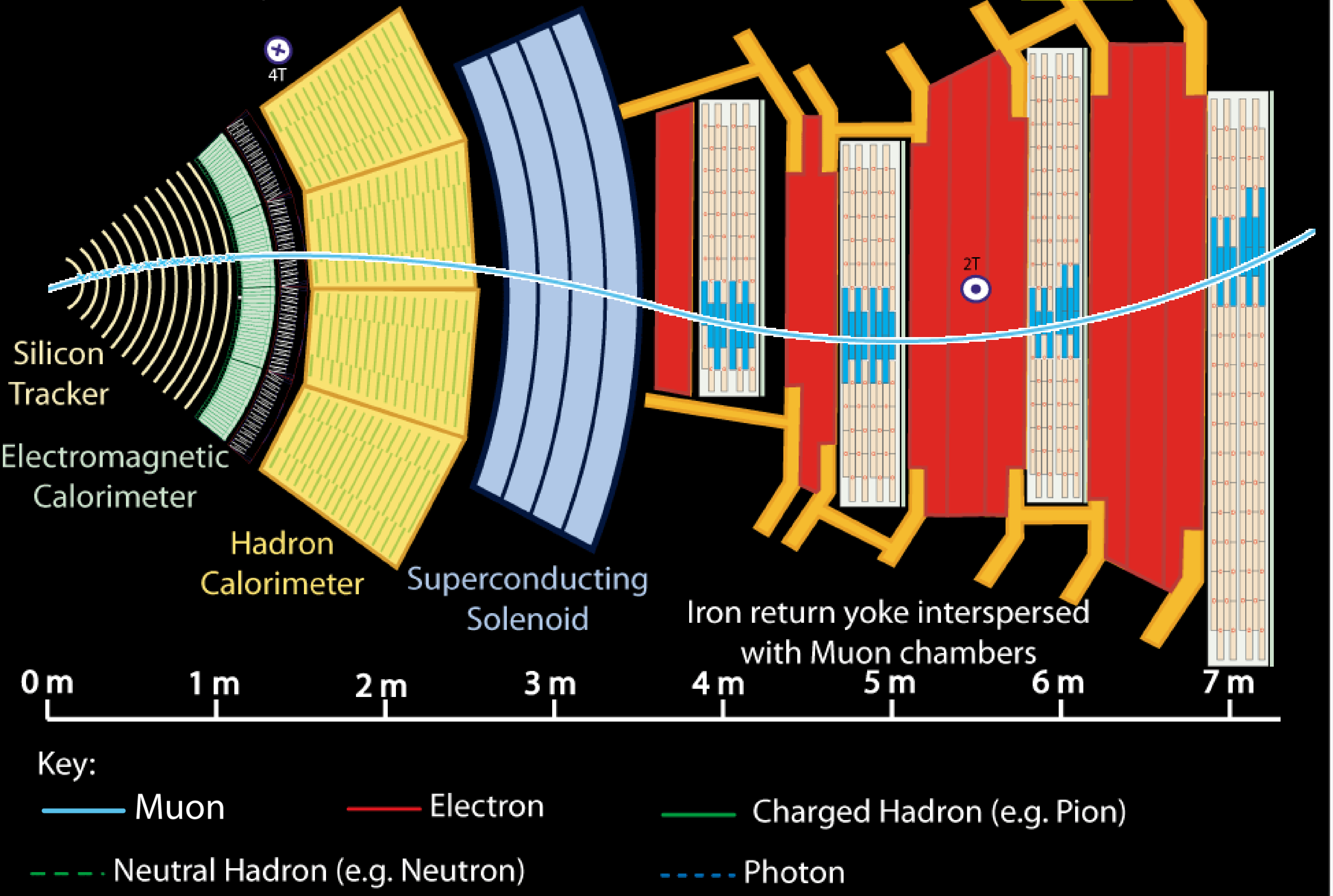
electromagnetic ***hadronic***
showers

momentum *measurement by curvature in magnetic field*

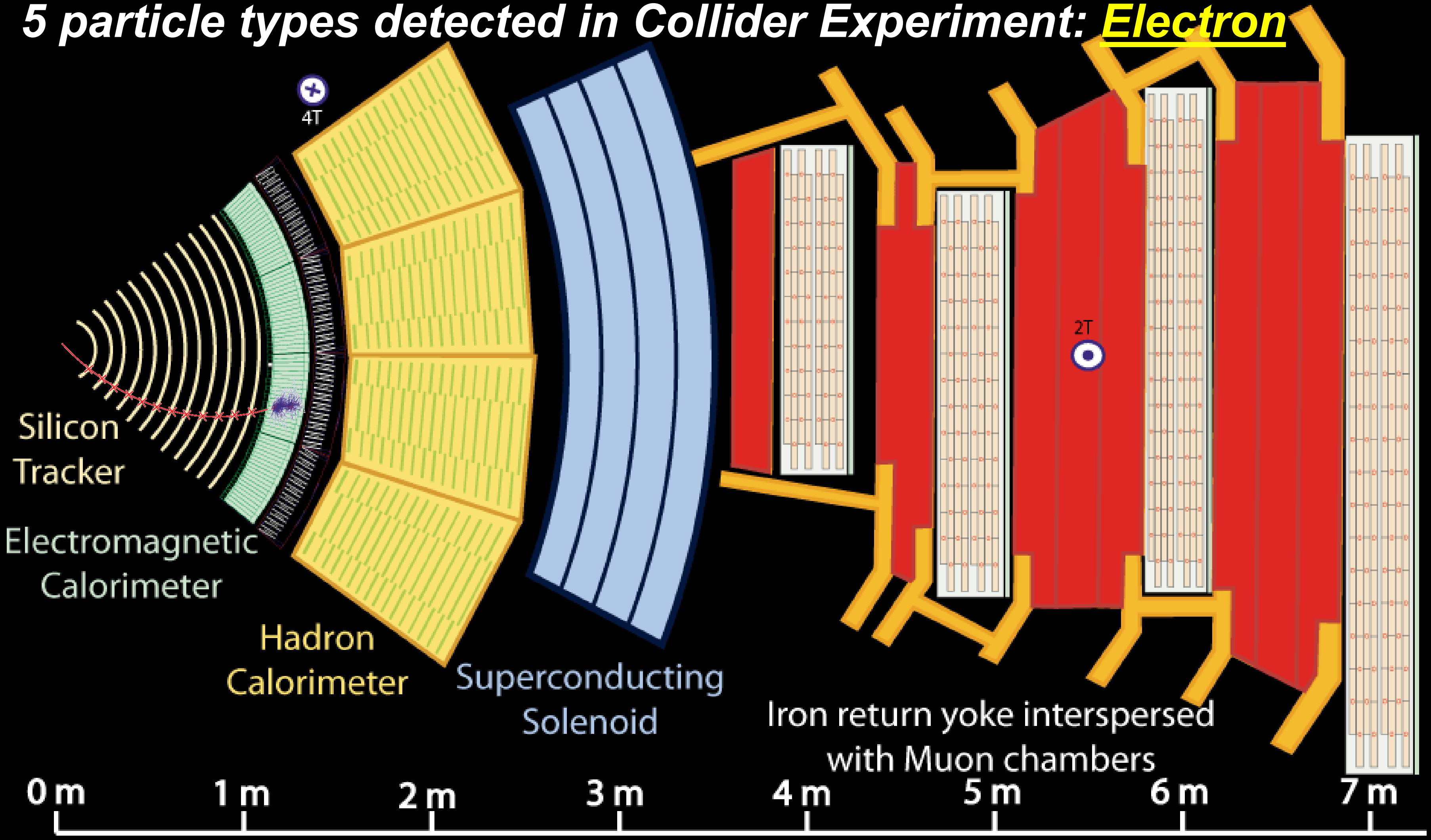
energy *measurement by creation and total absorption of showers*

muon detection with improved momentum measurement (long lever arm)

5 particle types detected in Collider Experiment: Muon



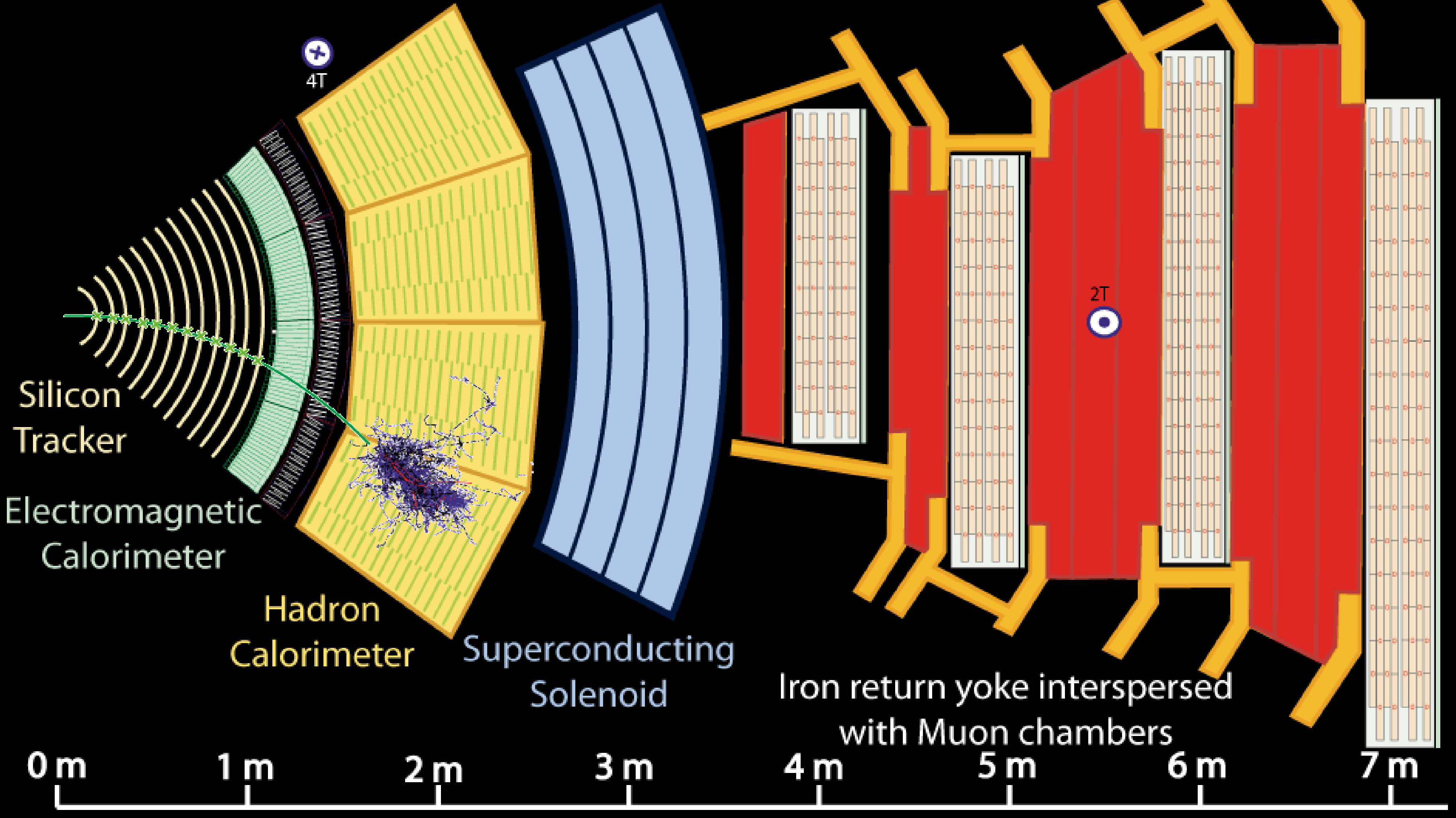
5 particle types detected in Collider Experiment: **Electron**



Key:

- —— Muon
- —— Electron
- —— Charged Hadron (e.g. Pion)
- - - - Neutral Hadron (e.g. Neutron)
- - - - Photon

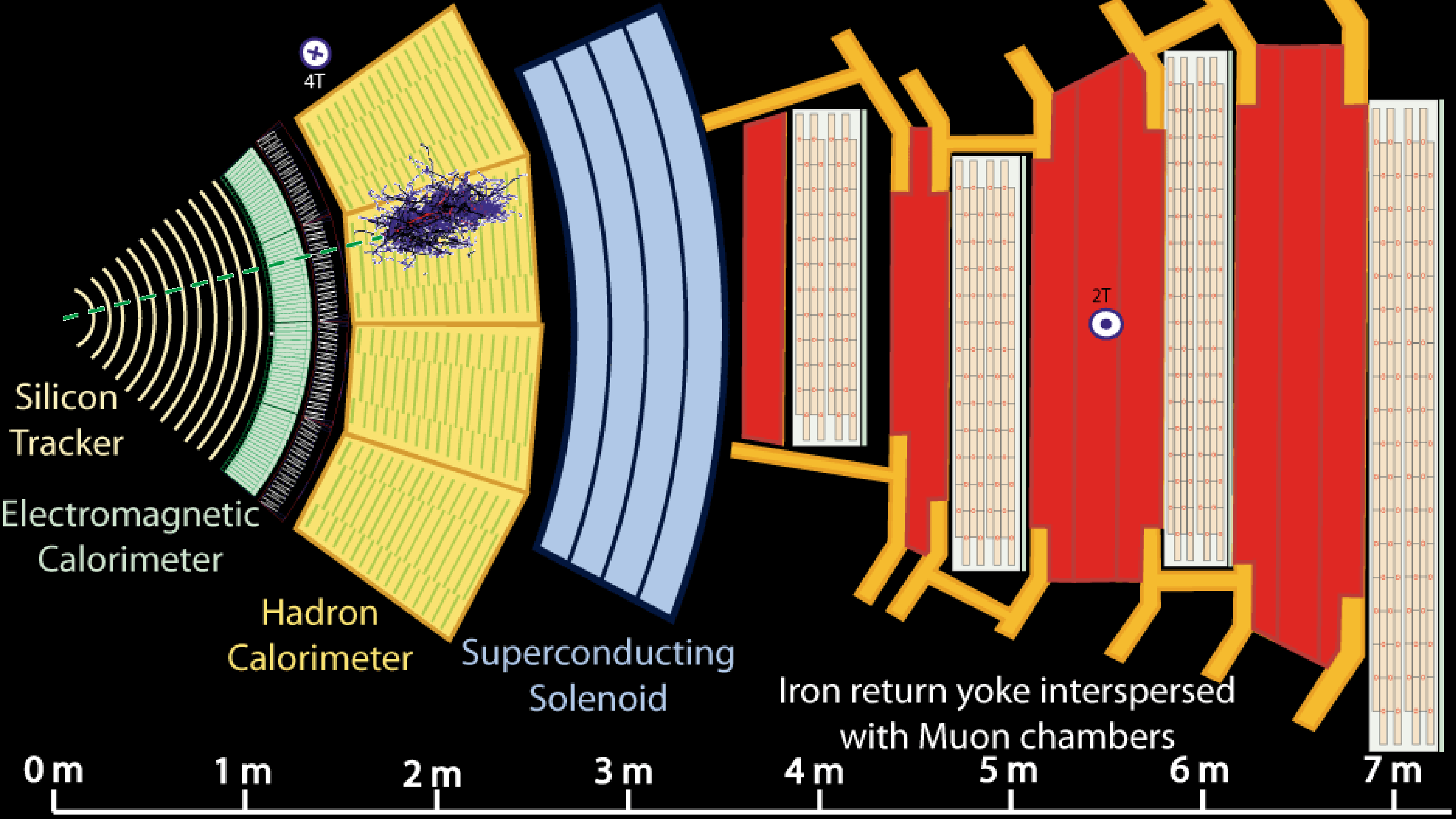
5 particle types detected in Collider Experiment: Charged Hadron



Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

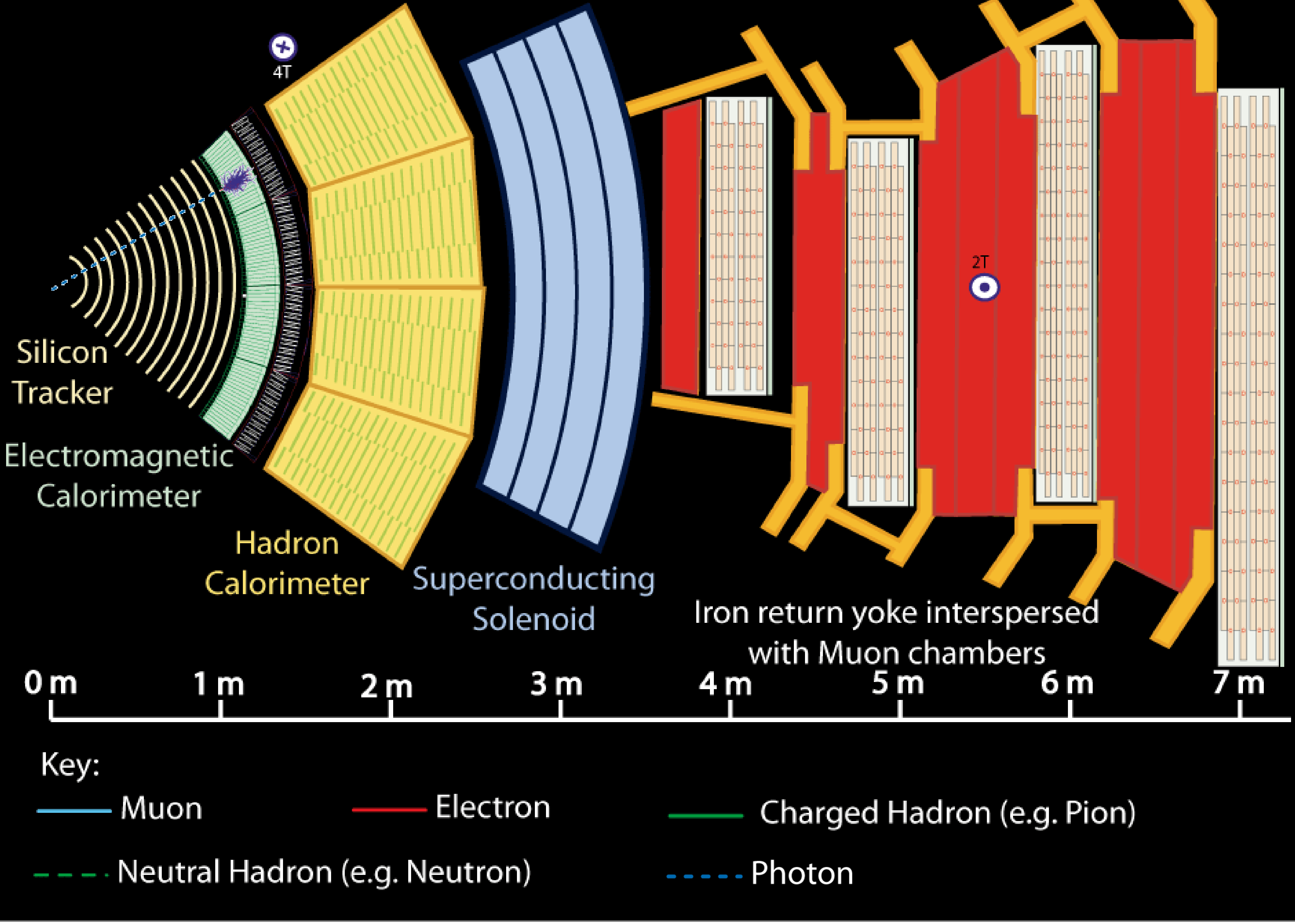
5 particle types detected in Collider Experiment: Neutral Hadron



Key:

—	Muon
—	Electron
—	Charged Hadron (e.g. Pion)
- - -	Neutral Hadron (e.g. Neutron)
- - - -	Photon

5 particle types detected in Collider Experiment: Photon



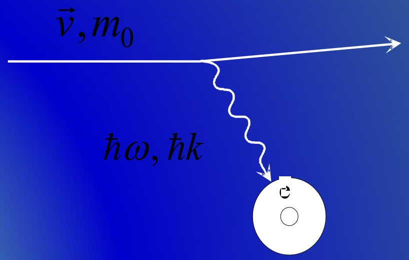
Charge Particle Interactions

✓ **(Multiple) elastic scattering with atoms of detector material**

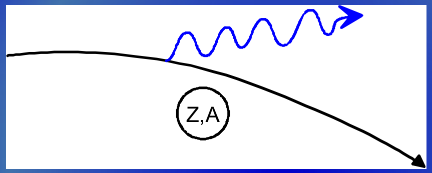
mostly unwanted, changes initial direction, affects momentum resolution

✓ **Ionization**

the basic mechanism in tracking detectors



✓ **Photon radiation**



- ***Bremsstrahlung***

  initiates electromagnetic shower in calorimeters, unwanted in tracking detectors

- ***Čerenkov radiation*** *(*Contribute very little to the energy loss < 5%)

  hadronic particle identification

  also in some homogeneous electromagnetic calorimeters (lead glass)

- ***Transition radiation*** *(*Contribute very little to the energy loss < 5%)

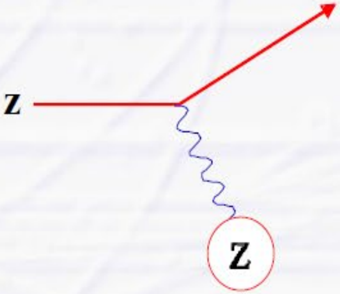
  electron identification in combination with tracking detector

✓ **Excitation**

Creation of scintillation light in calorimeters (plastic scintillators, fibers)

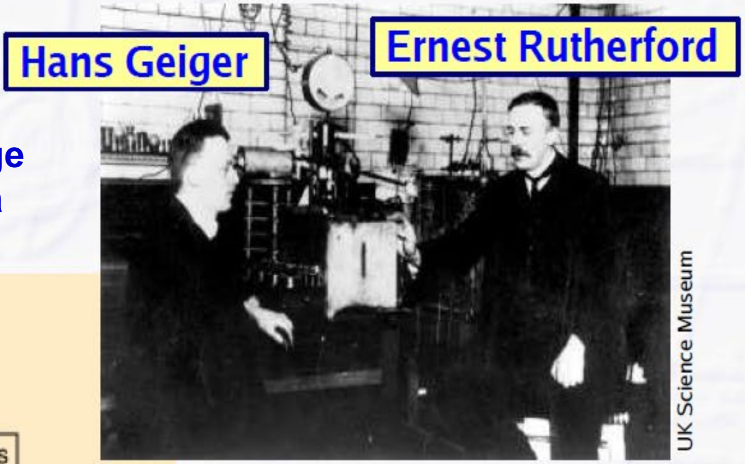
Elastic Scattering

- Most basic interaction of a charged particle in matter
  - elastic scattering with a nucleus
    = Rutherford (Coulomb) scattering

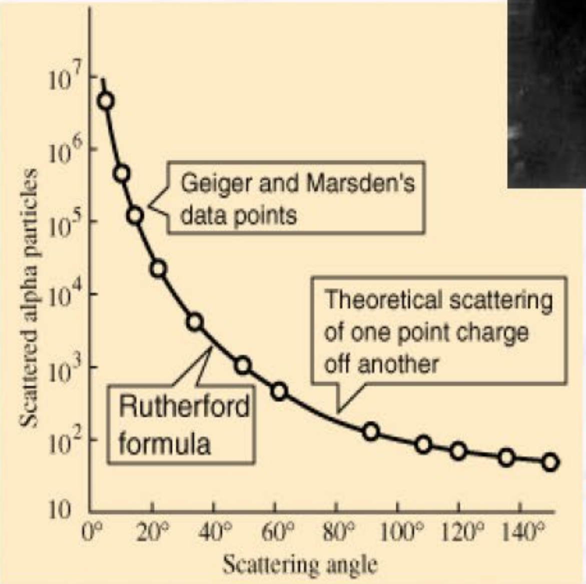


An incoming particle with charge *z* interacts elastically with a target of nuclear charge Z.

$$\frac{d\sigma}{d\Omega} = 4\, zZ r_e^2 \left(\frac{m_e c}{\beta p}\right)^2 \boxed{\frac{1}{\sin^4\Theta/2}}$$



UK Science Museum

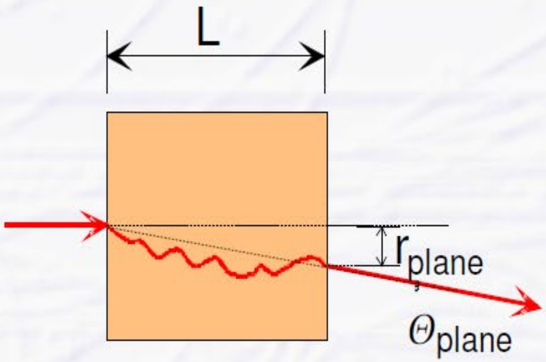


UK Science Museum

- Approximations
  - non-relativistic
  - no spins
- Scattering angle and energy transfer to nucleus usually small
  - No (significant) energy loss of the incoming particle
  - Just change of particle direction

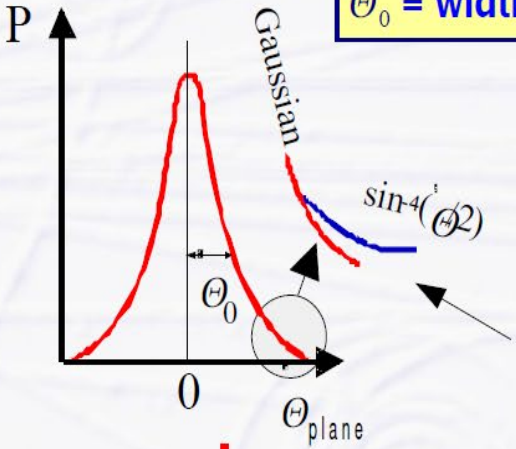
Multiple Scattering

- **If thick material layer: Multiple scattering**
  - after passing layer of thickness L particle leaves with some displacement r_{plane} and some deflection angle Θ_{plane}



distribution of deflection angle

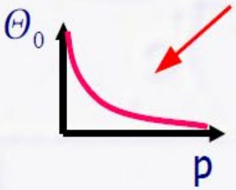
Θ_0 = width of distribution

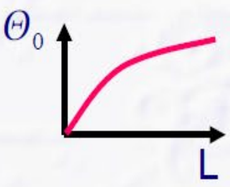


Gaussian is good approximation (except for tails)

- **Multiple scattering dominates momentum measurement for low momenta (see later)**

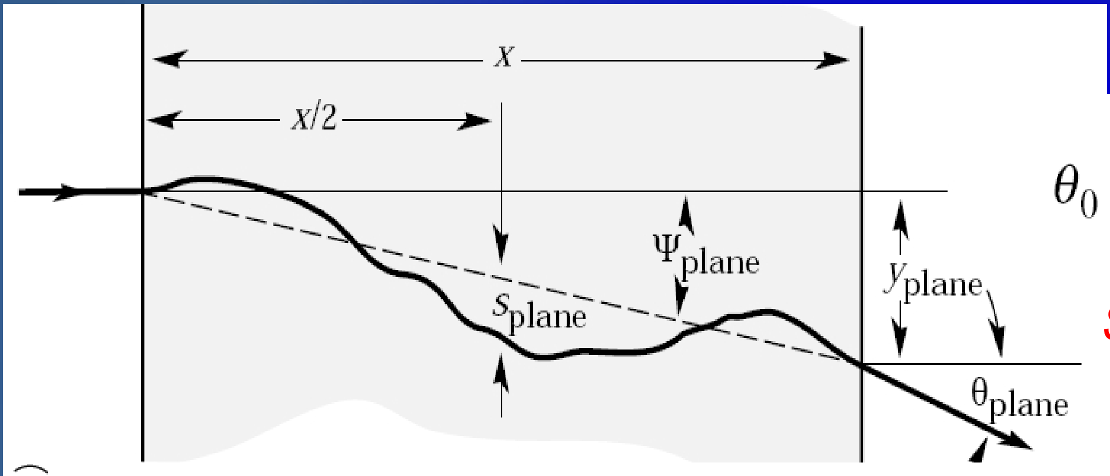
$$\Theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$





Multiple Scattering

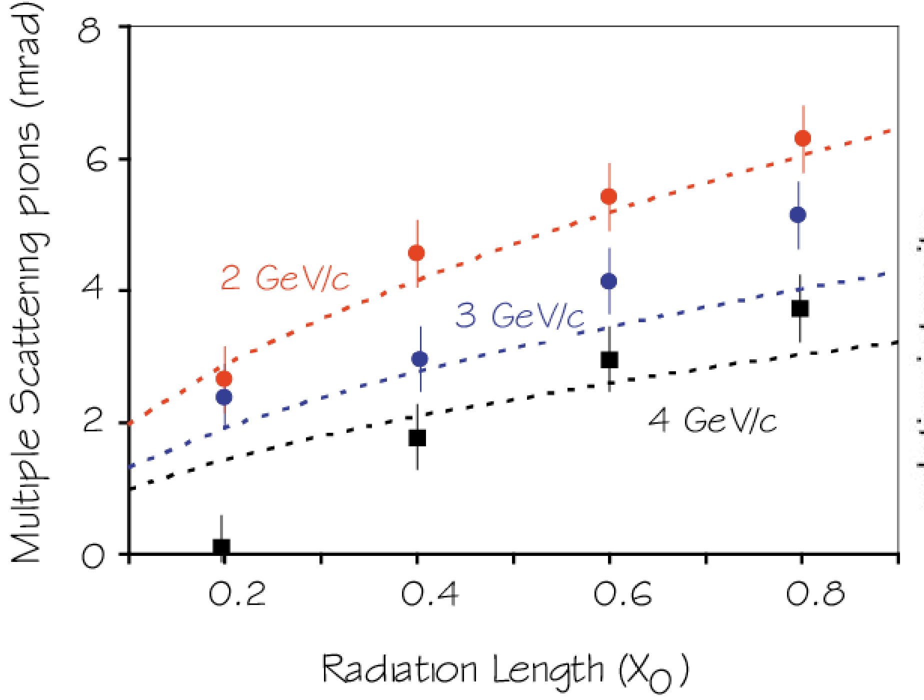
Precision of track reconstruction (and also combinatorial background, ghosts etc) from hits in tracking layers is often limited by multiple scattering

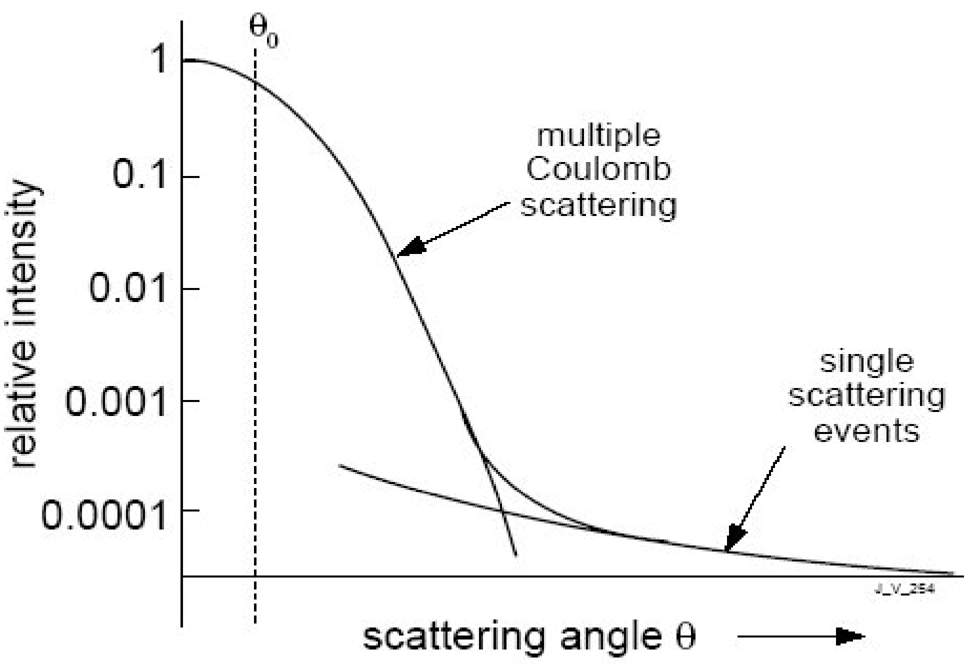


➔ ***Minimum of material***

$$\theta_0 = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{L}{X_0}}\left\{1+0.038\ln\left(\frac{L}{X_0}\right)\right\}$$

Smaller for high energy,
for small material depth,
for large radiation length.





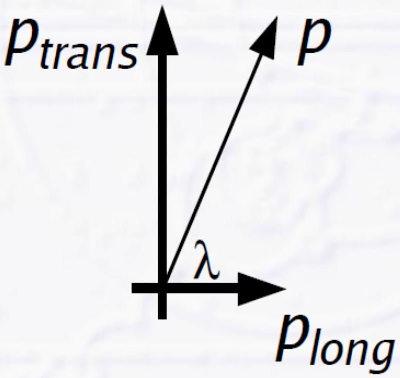
Momentum Measurement in a Magnetic Field

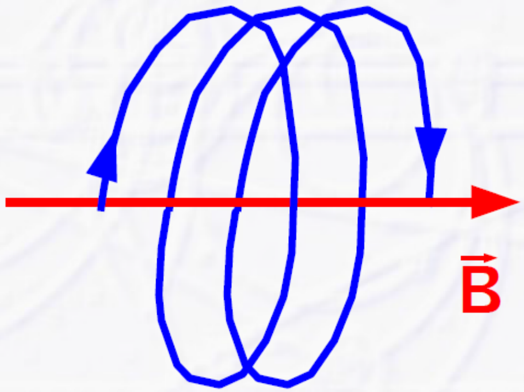
- **Charged particles are deflected by magnetic fields**
  - homogeneous B-field → particle follows a circle with radius r

$$\boxed{p_t\,[GeV/c] = 0.3 \cdot B\,[T] \cdot r\,[m]}$$

measuement of p_t via measuring the radius

  - this is just the momentum component ⊥ to the B-field
    transverse momentum p_t
  - no particle deflection parallel to magnetic field
  - if particle has longitudinal momentum component
    → particle follows a helix

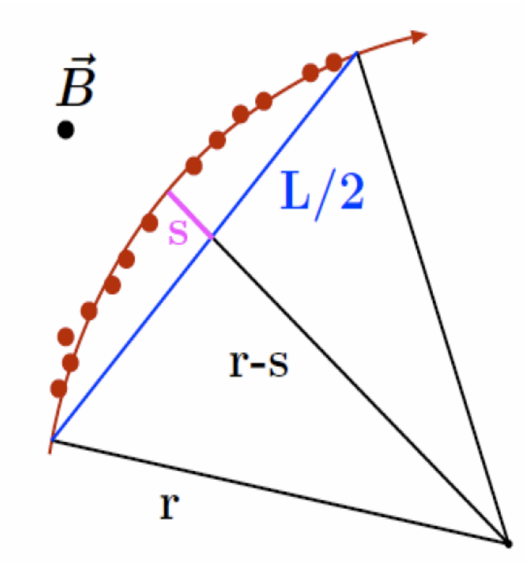




total momentum p to be measured via dip angle λ

$$p = \frac{p_t}{\sin\lambda}$$

Momentum Measurement in a Magnetic Field



- In real applications usually only slightly bent track segments are measured
  - Figure of merit: Sagitta

Segment of a circle: $s = r - \sqrt{r^2 - \frac{L^2}{4}}$

$$\Rightarrow r = \frac{s}{2} + \frac{L^2}{8s} \approx \frac{L^2}{8s} \quad (s \ll L)$$

With the radius-momentum-B-field relation: $r = \frac{p_T}{0.3\,B} \Rightarrow s = \frac{0.3\,B\,L^2}{8\,p_T}$

In general, for many measurement points:

- *Weak dependence on number of measurements: sqrt(1/N)*

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)}{0.3\,B\,L^2}\sqrt{720/(N+4)}\,p_T$$

- ➠ Je larger the magnetic field B, the length L and the number of measurement points, and the better the spacial resolution, the better is the momentum resolution
  ex.: N =7, L = 0.5, B = 2T, σ(x) = 20 μm, p_t = 5 GeV/c:
  $\Delta p_t / p_t$ = 0.5 %, r = 8.3 m, s = 3.75 mm

(Heavy) Charge Particle Energy Loss Due to Ionization

Bethe-Bloch formula

Many equivalent parameterizations in the literature

Quantum mechanic calculation of Bohr stopping power

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, p, m

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

$= 0.1535$ MeV cm^2/g

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

Fundamental constants

r_e=classical radius of electron
m_e=mass of electron
N_a=Avogadro's number
c =speed of light

Absorber medium

I = mean ionization potential
Z = atomic number of absorber
A = atomic weight of absorber
ρ = density of absorber
δ = density correction
C = shell correction

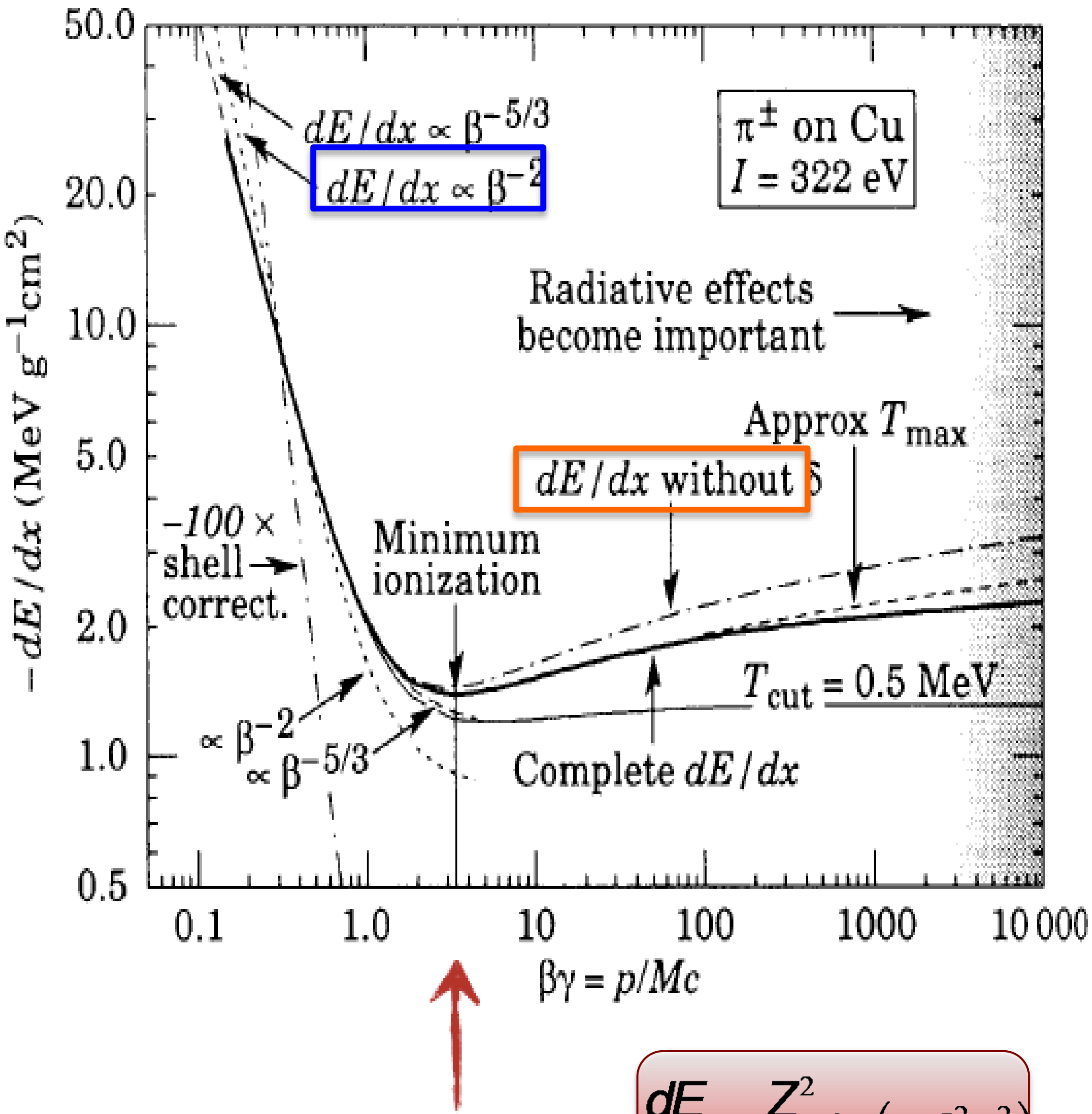
Incident particle

z = charge of incident particle
β = v/c of incident particle
γ = $(1-\beta^2)^{-1/2}$
W_{max}= max. energy transfer in one collision

Note: the classical dE/dx formula contains many features of the QM version: $(z/b)^2$, & ln[]

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

(Heavy) Charge Particle Energy Loss Due to Ionization



$\beta\gamma = 3\text{-}4$

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

Bethe-Bloch formula

Minimum ionizing particles (MIP): $\beta\gamma = 3\text{-}4$

dE/dx falls ~ β^{-2}; kinematic factor
[precise dependence: ~ $\beta^{-5/3}$]

dE/dx rises ~ $\ln(\beta\gamma)^2$; relativistic rise
[rel. extension of transversal E-field]

Saturation at large (βγ) due to density effect (correction δ)
[polarization of medium]

Units: MeV g^{-1} cm^2

MIP looses ~ 13 MeV/cm
[density of copper: 8.94 g/cm^3]

(Heavy) Charge Particle Energy Loss Due to Ionization

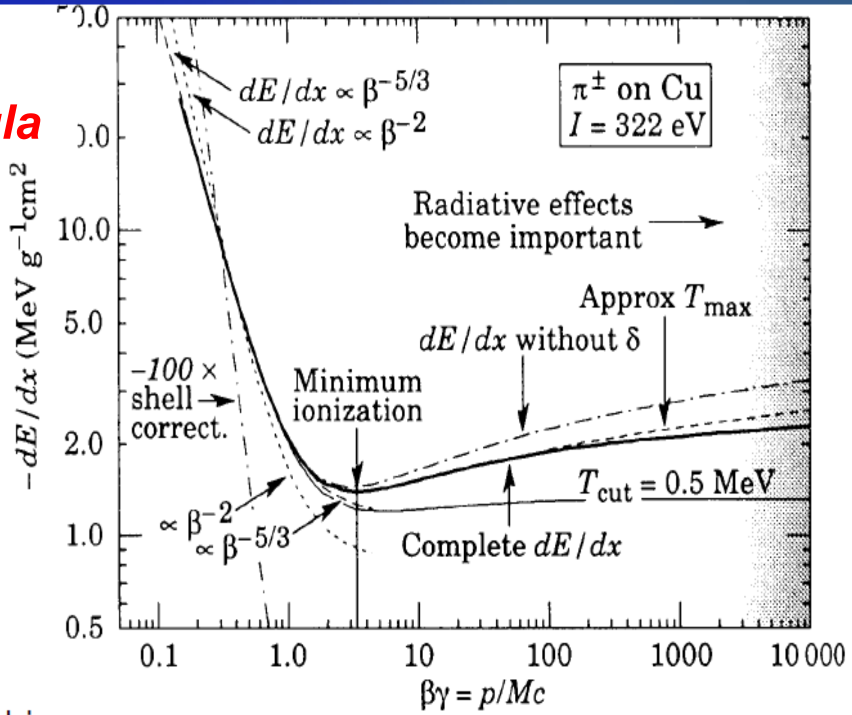
Understanding Bethe-Bloch formula

$1/\beta^2$-dependenc

Remember:

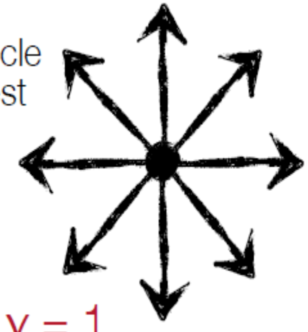
$$\Delta p_\perp = \int F_\perp dt = \int F_\perp \frac{dx}{v}$$

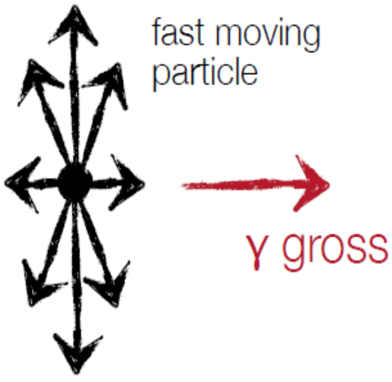
i.e. slower particles feel electric force of atomic electron for longer time ...



Relativistic rise for $\beta\gamma > 4$:

High energy particle: transversal electric field increases due to Lorentz transform; $E_y \rightarrow \gamma E_y$. Thus interaction cross section increases ...





Corrections:

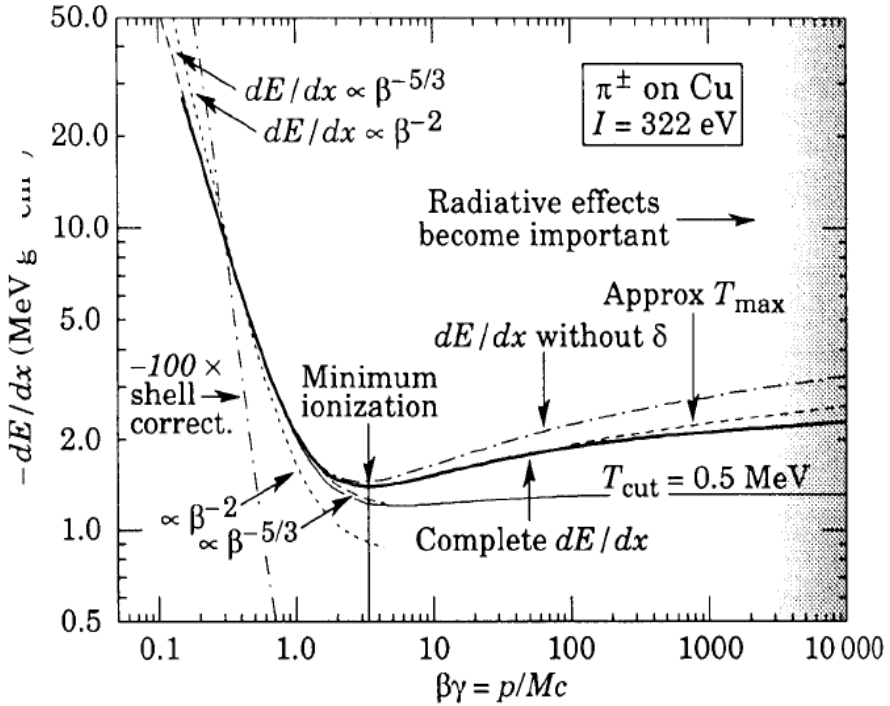
low energy : shell corrections

high energy : density corrections

(Heavy) Charge Particle Energy Loss Due to Ionization

Density correction:

Understanding Bethe-Bloch formula



Polarization effect ...
[density dependent]

→ Shielding of electrical field far from particle path; effectively cuts of the long range contribution ...

More relevant at high γ ...
[Increased range of electric field; larger b_{max}; ...]

For high energies:

$$\delta/2 \to \ln(\hbar\omega/I) + \ln\beta\gamma - 1/2$$

Density effect leads to saturation at high energy ...

Shell correction:

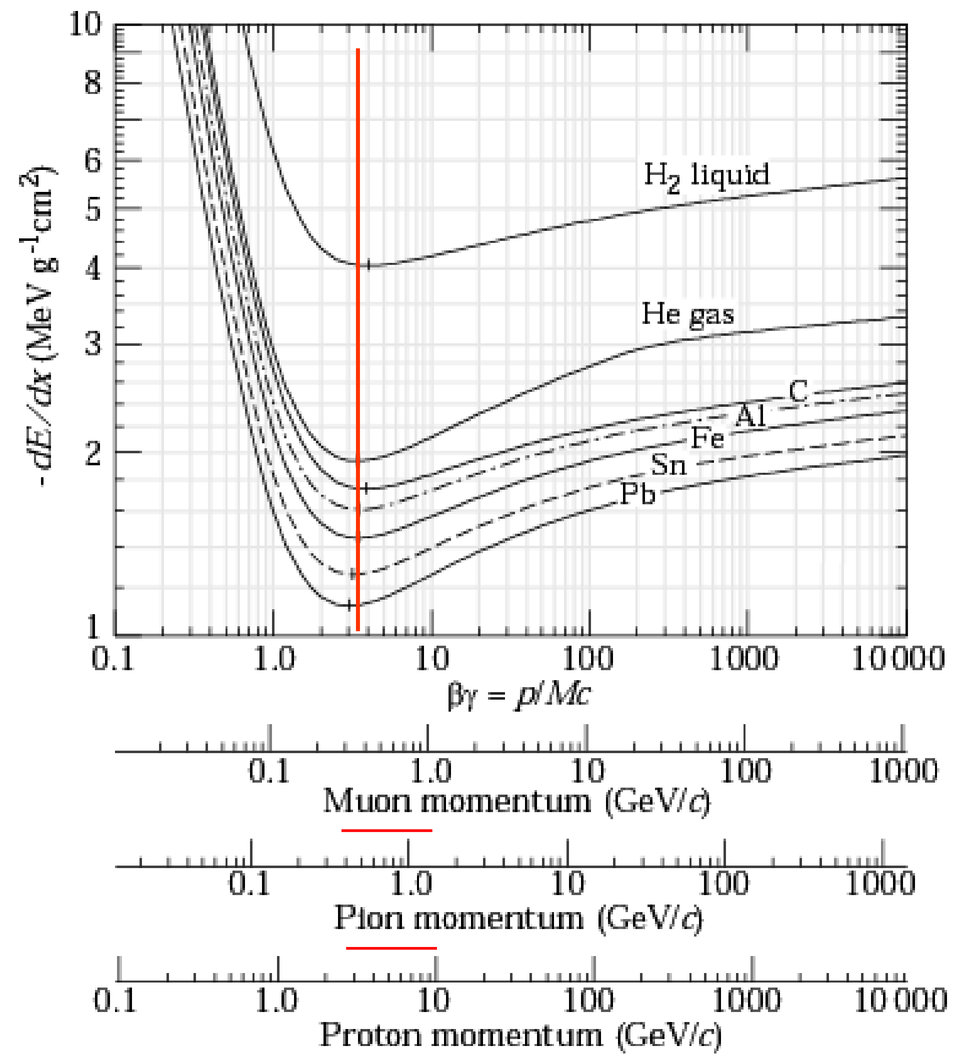
Arises if particle velocity is close to orbital velocity of electrons, i.e. βc ~ v_e.

Assumption that electron is at rest breaks down ...
Capture process is possible ...

Shell correction are in general small ...

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

dE/dx Minimum is Approximately Independent of the Material



Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.

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

- ✓ Dependence just on β (and Z/A).
- ✓ For p and π strong interactions with matter should also be considered. They become non-negligible at higher energy, and explain shower formation.
- ✓ For μ radiation losses occur starting from E(μ) = 100 GeV.
- ✓ For protons they start at even higher energy !

Minimum ionization:
ca. 1 - 2 MeV/g cm^{-2}

i.e. for a material with $\rho = 1$ g/cm^3 ➔ dE/dx = 1-2 MeV/cm

Example :
Iron: Thickness = 100 cm; ρ = 7.87 g/cm^3
dE ≈ 1.4 MeV g^{-1} cm^2 * 100 cm * 7.87g/cm^3 = 1102 MeV

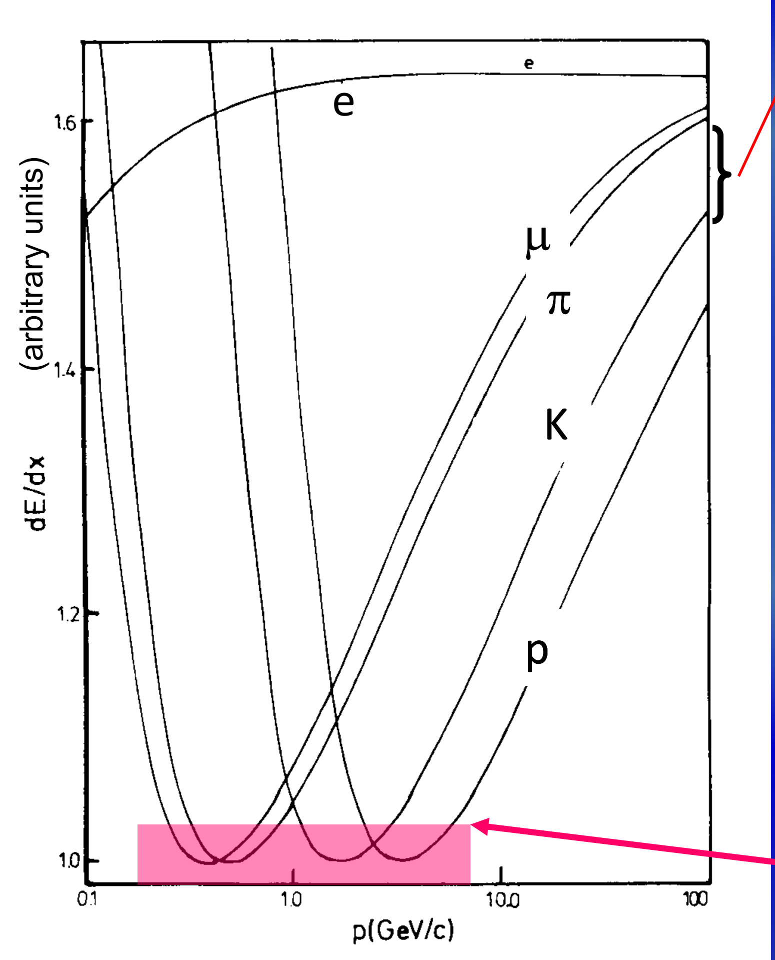
→ A 1 GeV Muon can traverse 1m of Iron

Particle ID from dE/dx for Charged Particles: Idea

$$p = m_0 \beta\gamma c$$

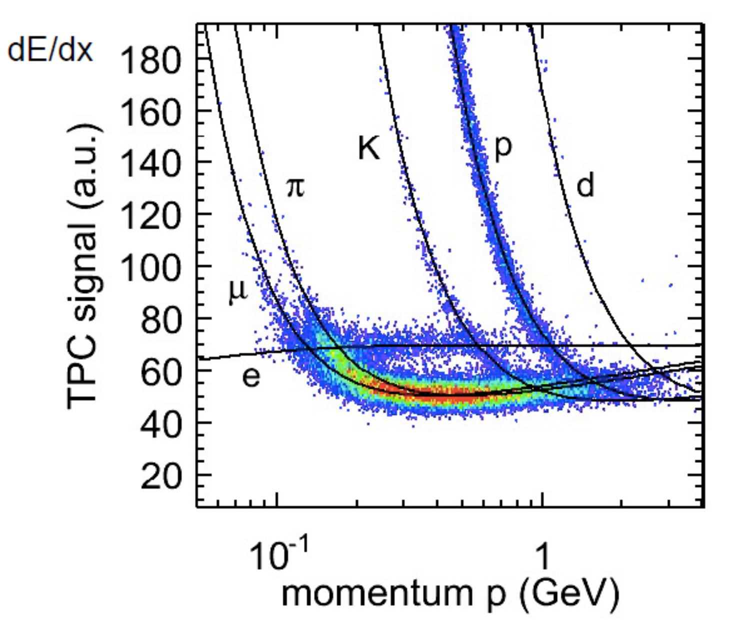
$$\frac{dE}{dx} \propto \frac{1}{\beta^2}\ln\left(\beta^2\gamma^2\right)$$

Simultaneous measurement of p and dE/dx defines mass m_0, hence the particle identity



Average energy loss for e, μ, π, K, p in 80/20 Ar/CH_4 (NTP) (J.N. Marx, Physics today, Oct.78)

***π/K* separation (2σ) requires a *dE/dx* resolution of < 5% (not so easy to achieve)**

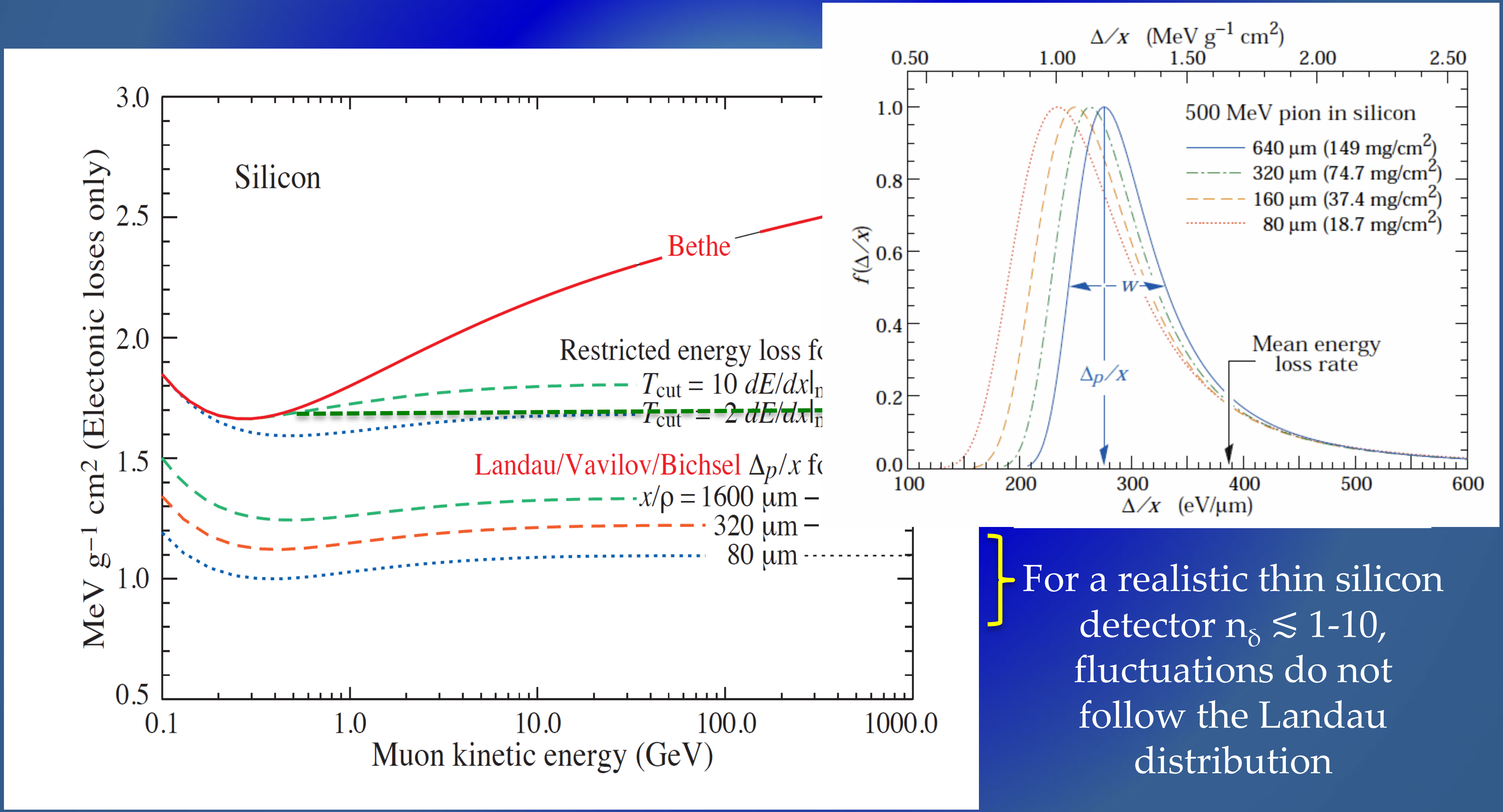


dE/dx is very similar for minimum ionizing particles

→ Energy loss fluctuates and shows Landau tails.

Dependence on Absorber Thickness

- The Bethe-Bloch equation describes the mean energy loss
- When a charged particle passes the layer of material with thickness x , the energy distribution of the δ-electrons and the fluctuations of their number (n_δ) cause fluctuations of the energy losses ΔE



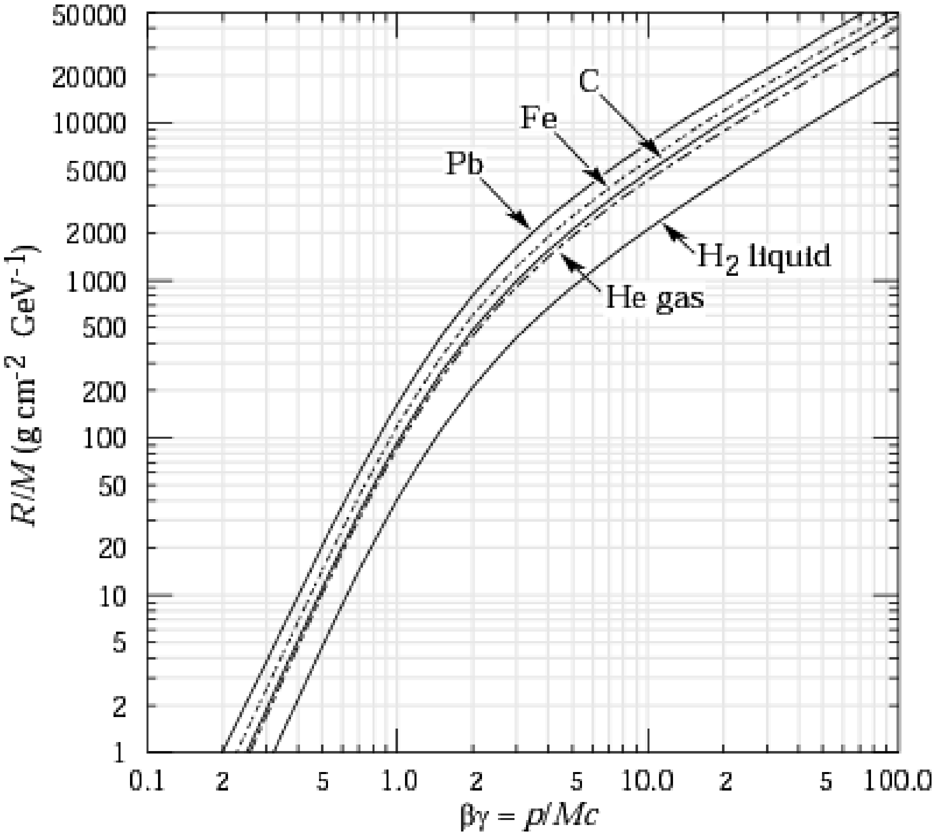
For a realistic thin silicon detector $n_\delta \lesssim$ 1-10, fluctuations do not follow the Landau distribution

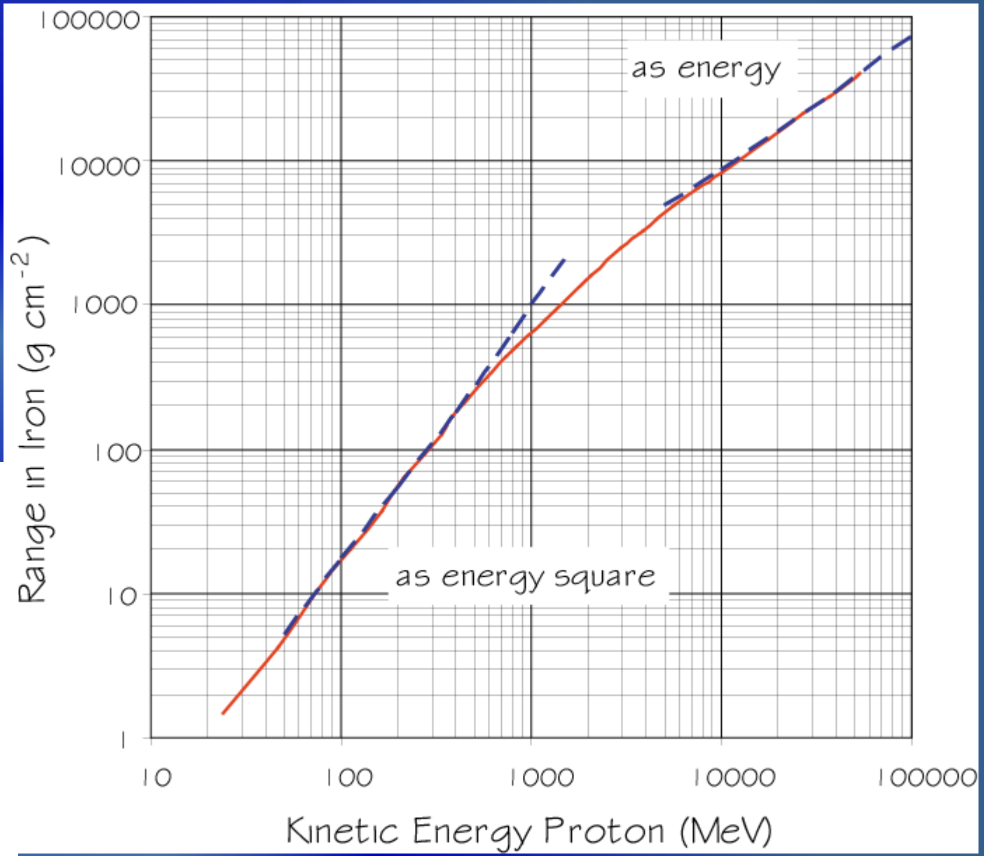
Mean Particle Range

Integrating dE/dX from Rutherford scattering and ignoring the slowly changing ln(term).

$$R(T) = \int_0^T \left[-\frac{dE}{dx} \right]^{-1} dE$$

More often use empirical formula



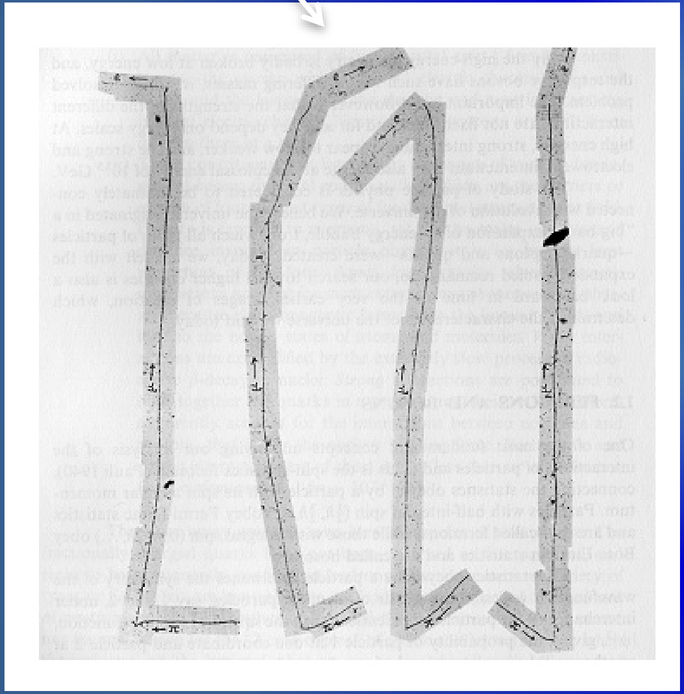


$$Range = R \approx \frac{Const.}{Z_1^2 m_1^2} E_{Kinetic}^2$$

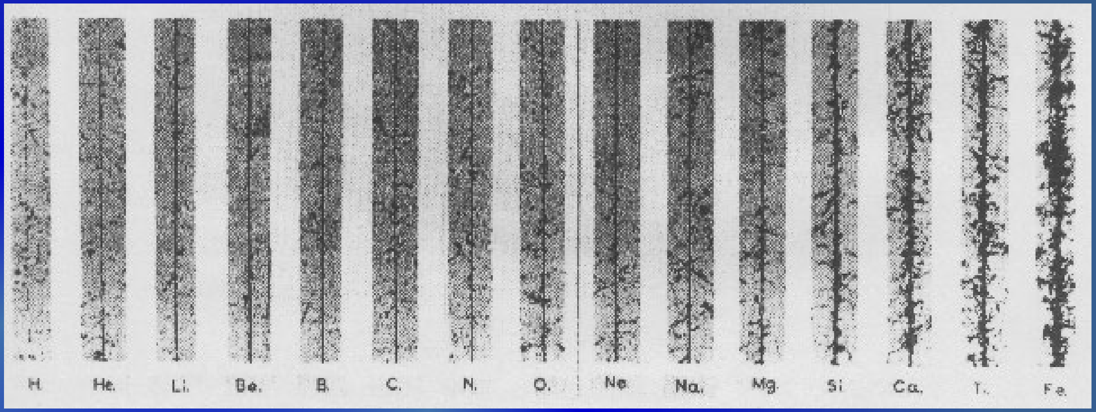
Range is approximately proportional to the kinetic energy square at low energy and approximately proportional to the kinetic energy at high energy where the dE/dX is about constant.

Energy Loss at Small Momenta

Small energy loss
→ Fast Particle

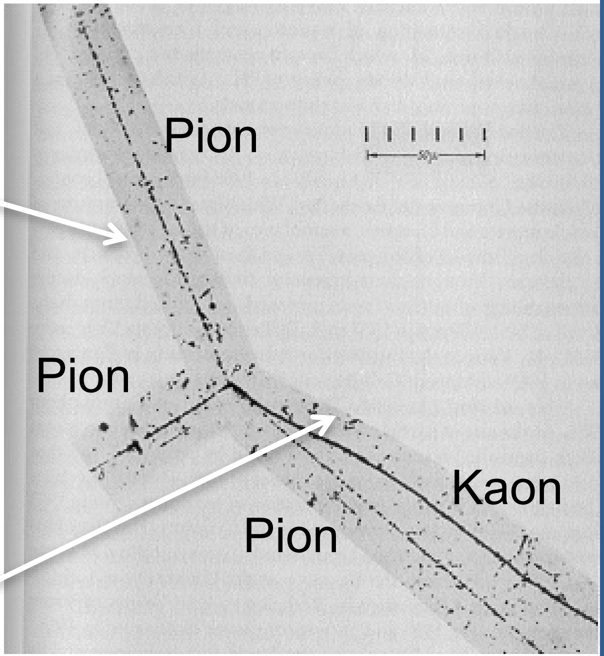


Discovery of muon and pion



Cosmis rays: dE/dx α Z^2

Small energy loss
→ Fast particle



Large energy loss
→ Slow particle

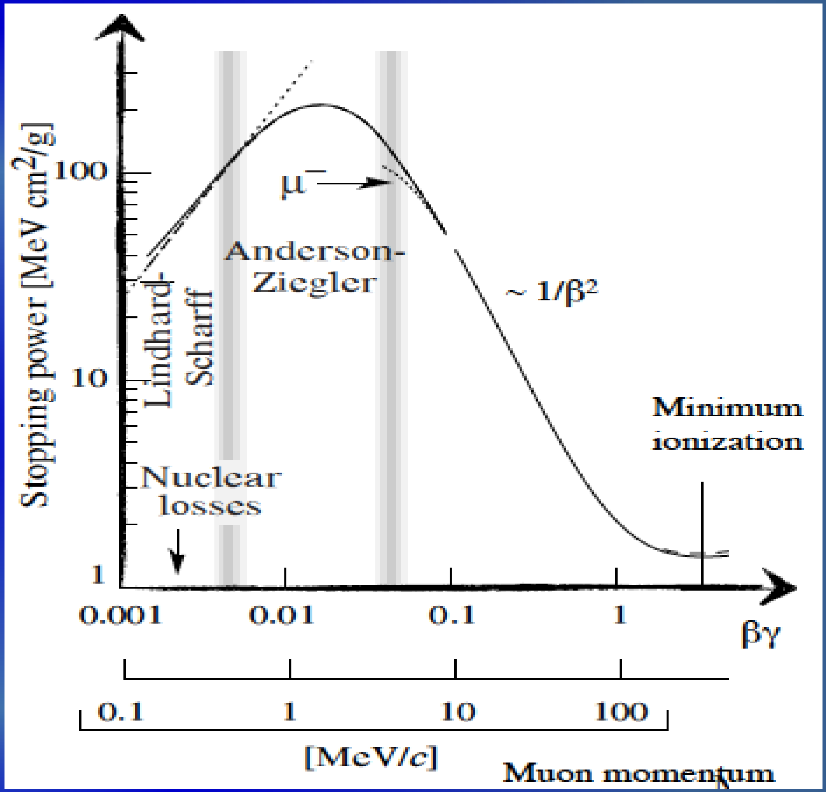
Energy Loss at Small Momenta

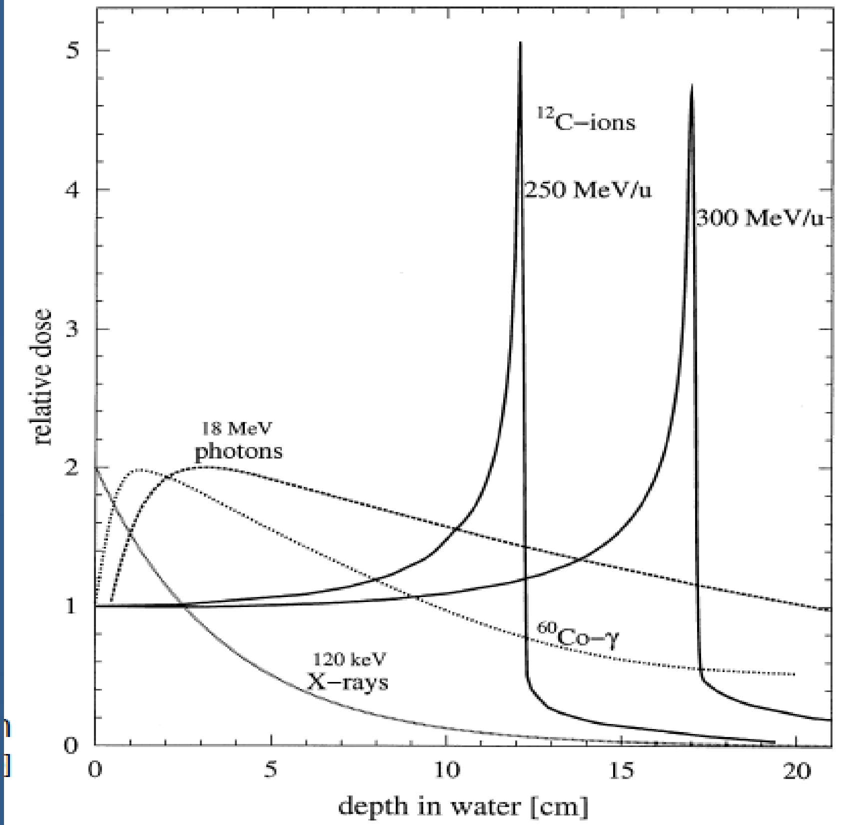
- ✓ energy loss increases at small $\beta\gamma$
- ✓ particles deposit most of their energy at the end of their track

➔ **Bragg peak**

Not used in HEP but is basic for medical application, hadron therapy

For $\beta\gamma < 0.05$ there are only phenomenological fitting formulae available.





➔ ***Important effect for tumor therapy***

Possibility to precisely deposit dose at well-defined depth by E_{beam} variation

Energy Loss dE/dx: Electrons (Positrons)

Electrons (and positrons) are different as they are light

→ Bethe-Bloch formula needs modification

→Incident and target electron have same mass

→ Scattering of identical, undistinguishable particles

Energy loss for electrons/positrons involve mainly two different physics mechanisms:

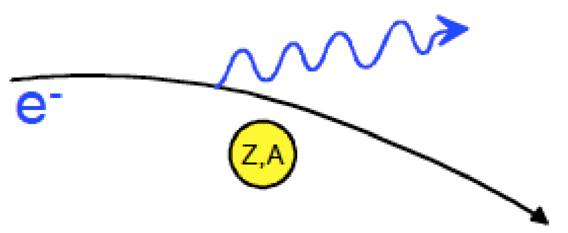
$$-\left\langle \frac{dE}{dx} \right\rangle_{Ionization} \propto \ln(E)$$

- **Excitation/ionization**

  But collision between identical particles + electron is now deflected

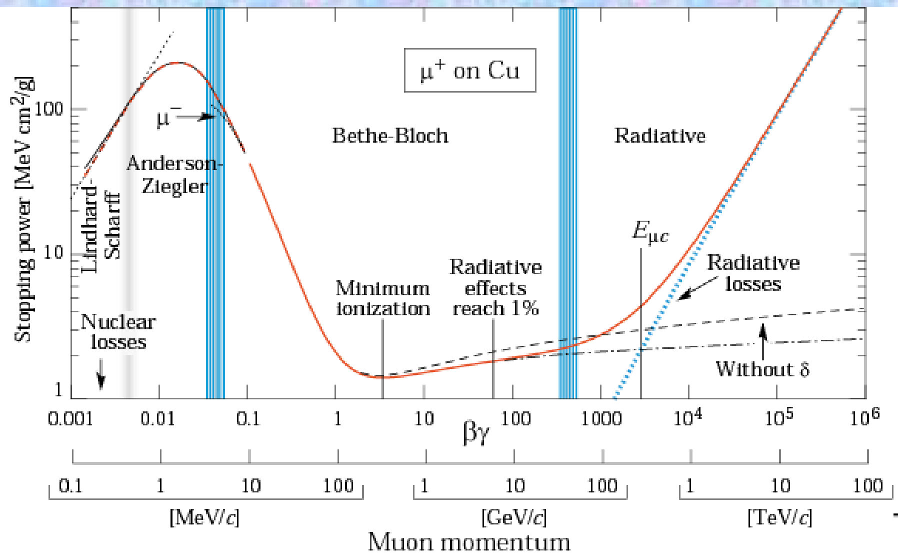
- **Bremsstrahlung : emission** of photon by scattering with the nucleus electrical field

  At high energies radiative processes dominate



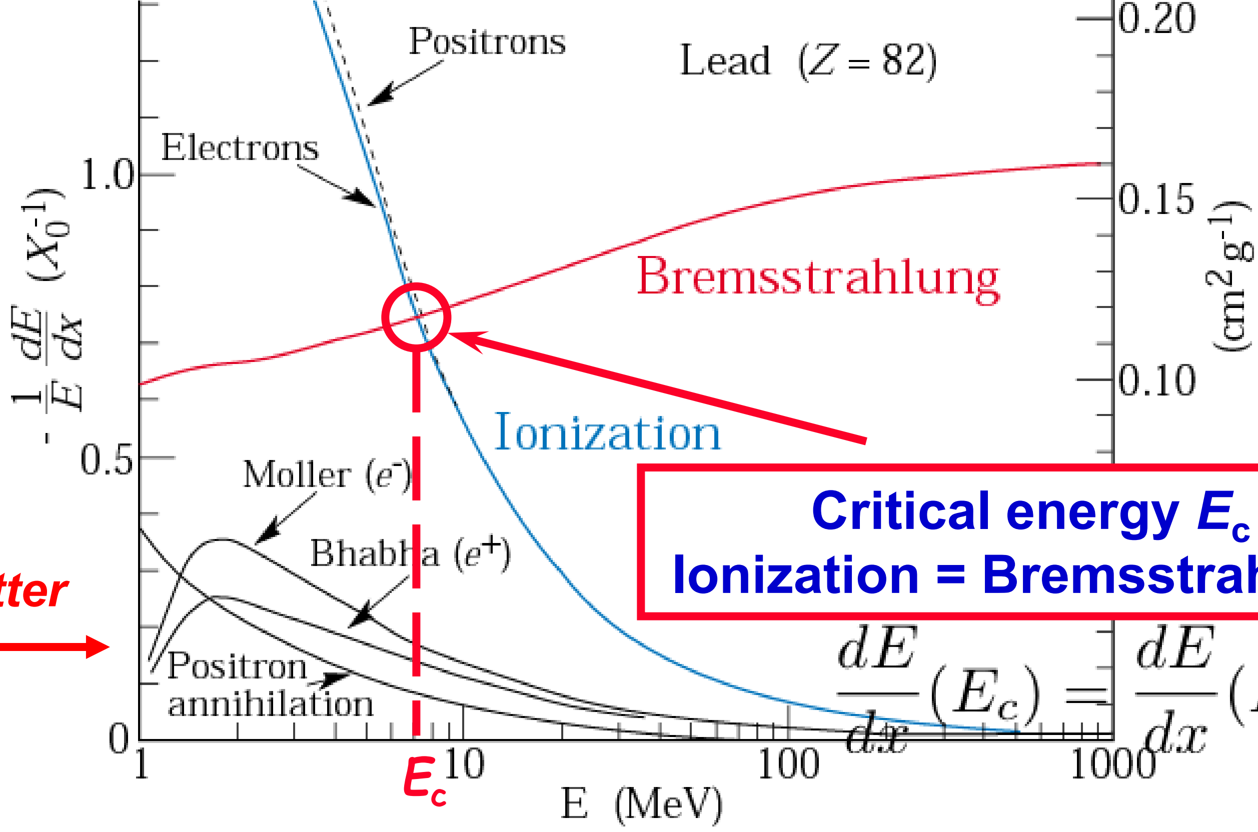
$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} \propto \frac{E}{m^2}$$

energy loss proportional to $1/m^2$ → main relevance for electrons (or ultra-relativistic muons)



Bethe-Bloch for heavy particles

$$Stopping\ Power \equiv \frac{dE}{dx} \equiv E \cdot \rho \frac{1}{X_0}$$



1.7 19.6 196 **βγ**

Electron (positron) interaction with matter

Critical energy E_c
Ionization = Bremsstrahlung

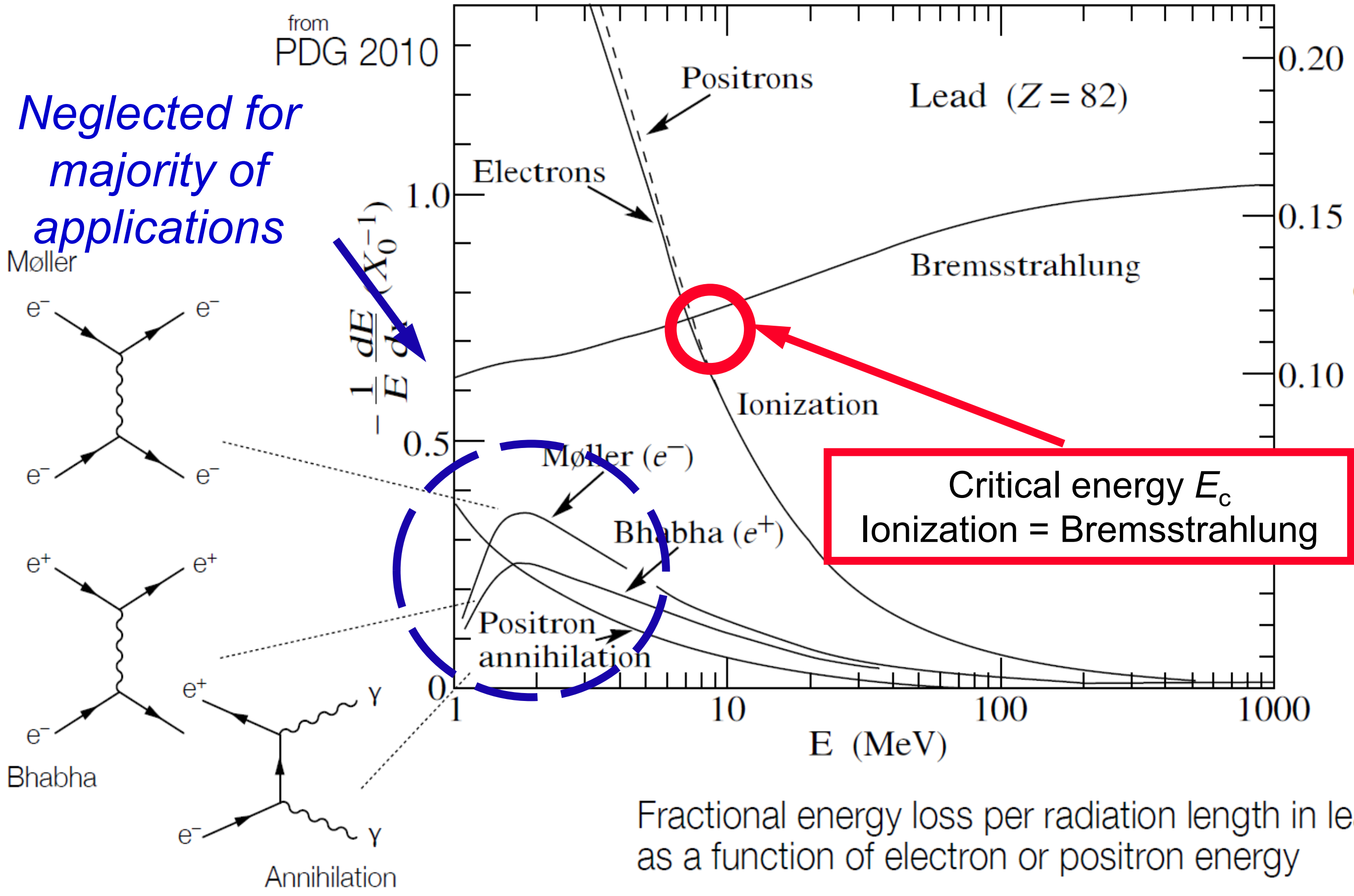
$$\frac{dE}{dx}(E_c) = \frac{dE}{dx}(E_c)$$

Total Energy Loss for Electrons

Define Radiation Length X_o → as the Radiative Mean Path :

i.e. the distance over which the energy of electron/positron is reduced by a factor e by Bremsstrahlung. Measured in units of [g/cm2]

Neglected for majority of applications



Critical energy E_c
Ionization = Bremsstrahlung

Fractional energy loss per radiation length in lead as a function of electron or positron energy

$$-\left\langle \frac{dE}{dx} \right\rangle_{Brems} = \frac{E}{X_0}$$

X_0 = radiation length in [g/cm^2]

$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

After passage of one X_0 electron has lost all but (1/e)th of its energy (63%)

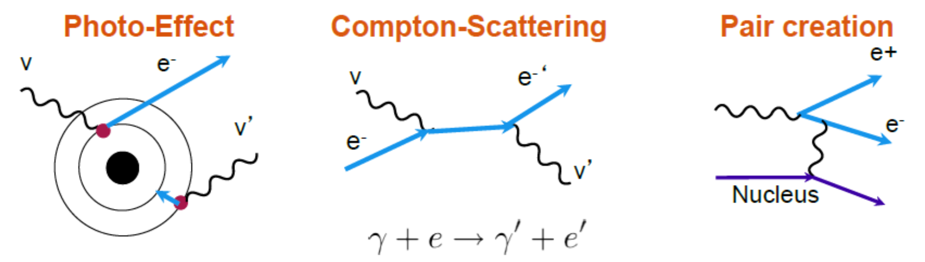
E_c = critical energy

$$\frac{dE}{dx}(E_c)\bigg|_{Brems} = \frac{dE}{dx}(E_c)\bigg|_{Ion}$$

Fractional energy loss per X_o in lead as a function of electron/positron energy

Energy Loss for Photons

Energy loss for photons →
three major physics mechanisms :



- ***Photo electric effect : absorption of a photon by an atom ejecting an electron***

$$\sigma = \boxed{Z^5}\alpha^4\left(\frac{m_e c^2}{E_\gamma}\right)^n \quad n = 7/2 \text{ for } E << m_e c^2 \text{ and} \rightarrow 1 \text{ for } E >> m_e c^2$$

Strong dependence with Z, dominant at low photon energy

- ***Compton scattering***

$$\sigma_C^e \propto \frac{\ln E_\gamma}{E\gamma} \text{ and atomic compton} = Z\,\sigma_C^e$$

- ***Pair creation (similar to bremsstrahlung) :*** dominant for E >> $m_e c^2$

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2\left(\frac{7}{9}\ln\frac{183}{Z^{\frac{1}{3}}}\right) = \frac{A}{N_A}\boxed{\frac{7}{9}\frac{1}{X_0}}$$

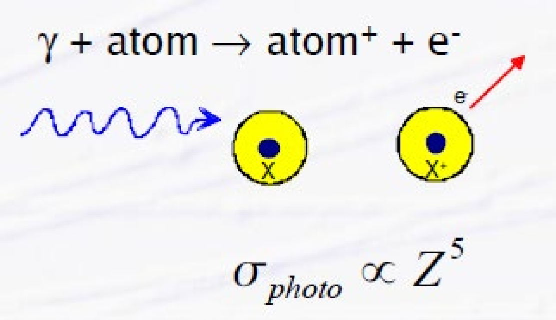
Independent of energy !

Probability of pair creation in 1 X_0 is $e^{-7/9}$, mean free path of a photon before creating a e^+e^- pair is $\Lambda_{pair} = 9/7\ X_0$

Particle Interactions: Photons

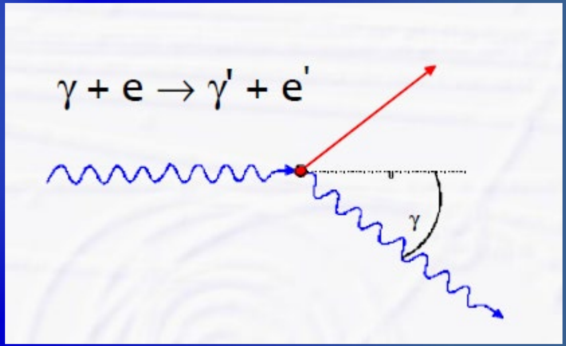
Photo effect

- used at various photo detectors to create electrons on photo cathodes in vacuum and gas or at semi conductors (surface)
    - Photo Multiplier Tubes (PMT)
    - Photo diodes



Compton scattering ($e^-\gamma$ scattering)

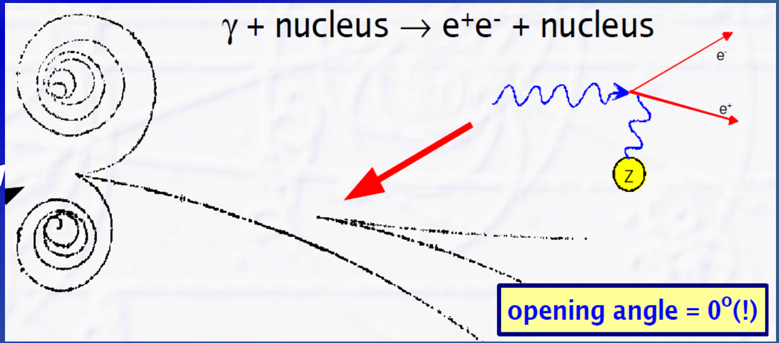
- not used for particle detection
    - was/is used for polarization measurement of beams at e^+e^- machines and could be used to create high energy photons in a gg - collider



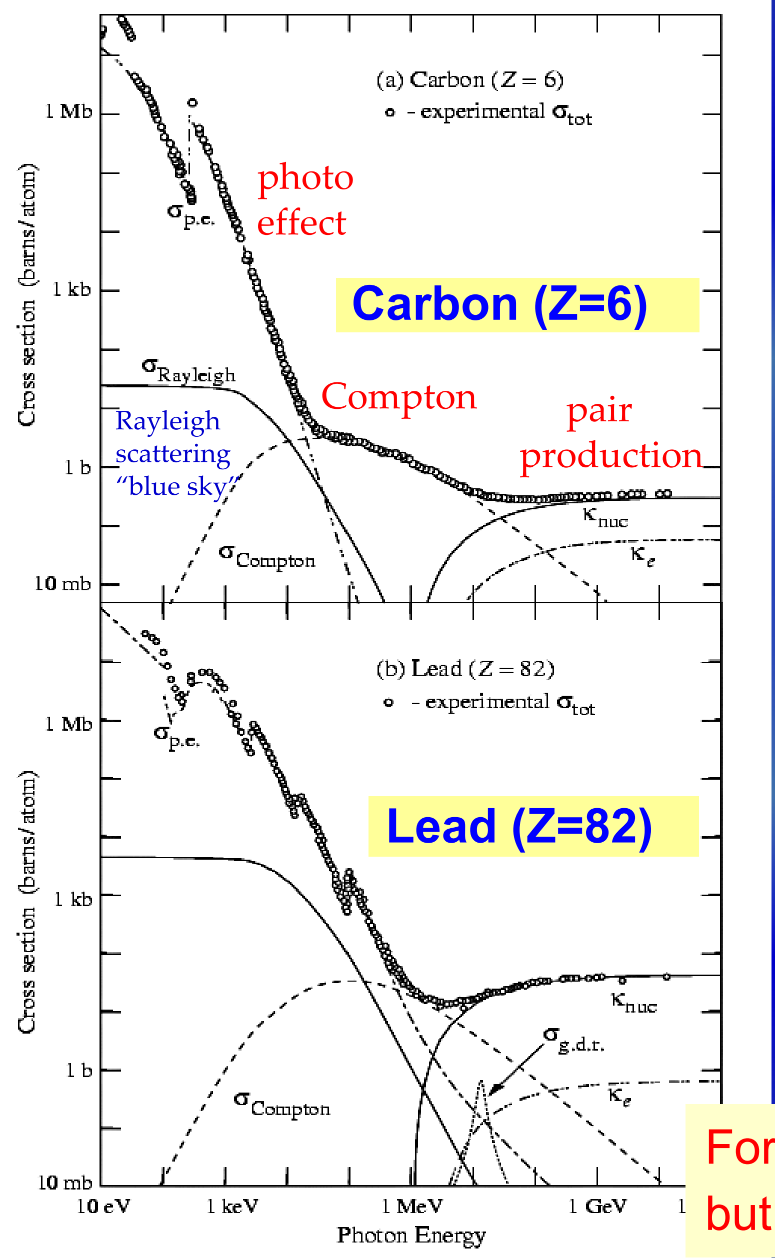
Pair production ($\gamma \rightarrow e^+e^-$)

- initiates electromagnetic shower in calorimeters, unwanted in tracking detectors

$\gamma + e^- \rightarrow e^+ e^- + e^- + \gamma$



Photon Interactions: Overview



- ***Photo effect dominating at low γ energies (< some 100 keV)***

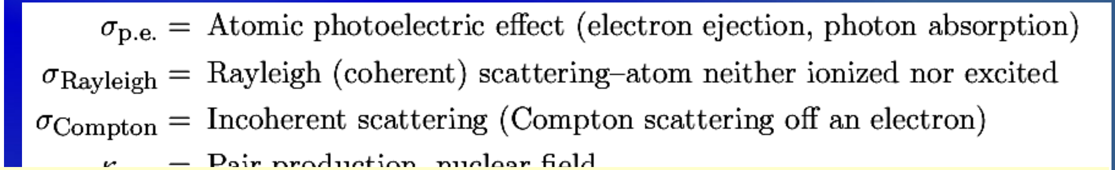
- ***Compton scattering regime ~ some 100 keV up to ~10 MeV***

  → **exact energy domain depends on Z**

  - low Z: wide energy range of Compton scat.

  - large Z: small energy range of Compton scat.

- ***Pair production dominating at high energies (> ~10 MeV)***

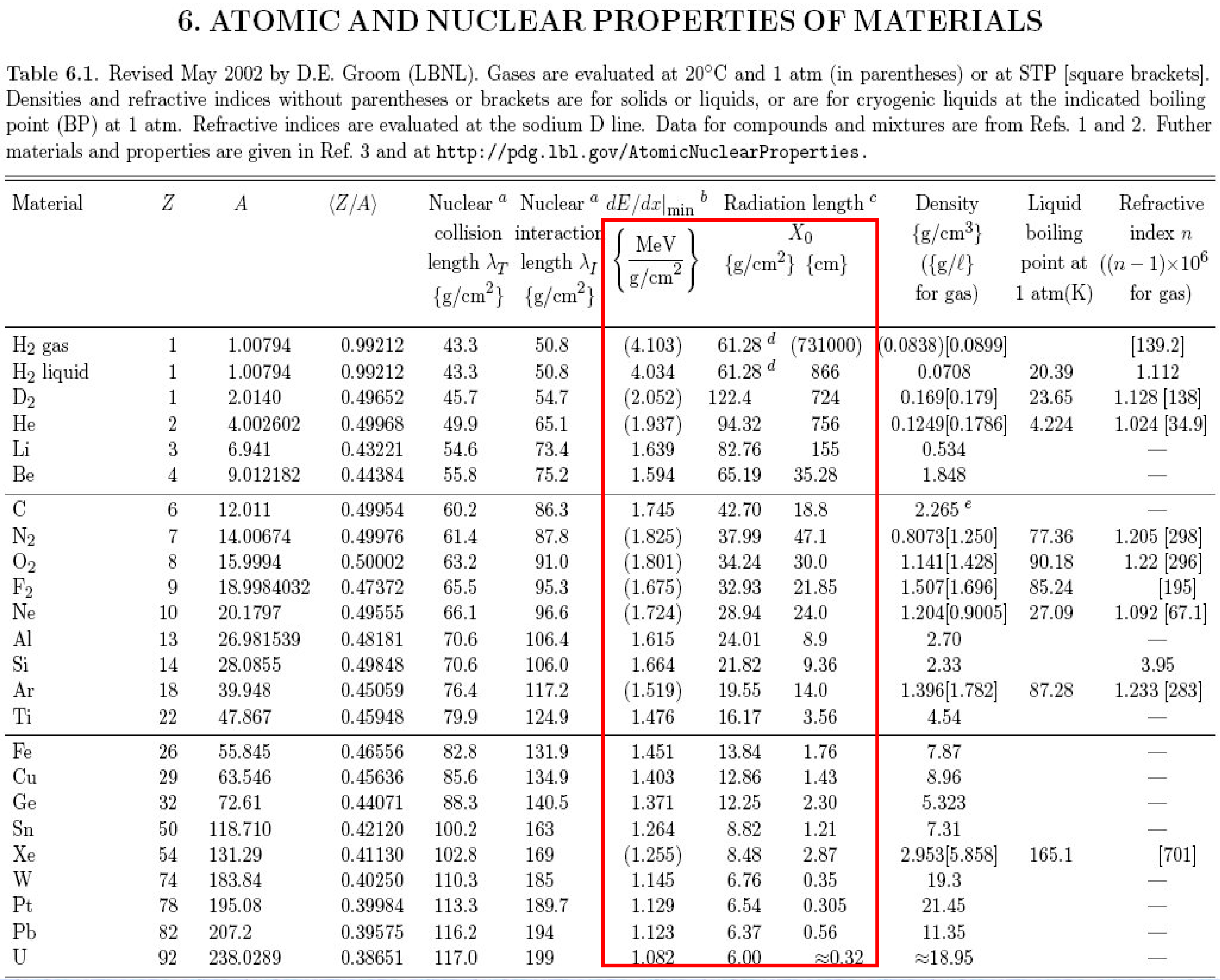


$\sigma_{\rm p.e.}$ = Atomic photoelectric effect (electron ejection, photon absorption)
$\sigma_{\rm Rayleigh}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited
$\sigma_{\rm Compton}$ = Incoherent scattering (Compton scattering off an electron)
κ = Pair production, nuclear field

For photons, it is not the energy, which is attenuated, but the intensity : photons are absorbed or deviated

Radiation Length (X_0)

- ***Main energy loss of high energy photons/electrons in matter***
  - pair production (γ) and bremsstrahlung ($e^{\pm}$)
- ***Can characterize any material by its radiation length X_0***
  - 2 definitions (for electrons and for photons)
    - X_0 = length after an electron looses all but 1/e of its energy by Bremsstrahlung
    - X_0 = 7/9 of mean free path length for pair prodution by the photon
- ***Very convienient quantity***
  - Rather than using thickness, density, material type etc. detector
    - often expressed as % of X_0
  - ***tracking detectors should have X_0 as low as possible (<< 1 X_0)***
    - ATLAS and CMS trackers: 30% - 130% X_0
    - not really "transparent", high probability to initiate electromagnetic showers in tracker far before electrons/photons reach calorimeters
      - "pre-shower" detectors in front of calorimeter should detect and correct measured ECAL energy for such early showers
  - ***calorimeters should have X_0 as high as possible (typically 20...30 X_0)***



6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T $\{\mathrm{g/cm^2}\}$	Nuclear [a] interaction length λ_I $\{\mathrm{g/cm^2}\}$	$dE/dx\vert_{\mathrm{min}}$ [b] $\left\{\frac{\mathrm{MeV}}{\mathrm{g/cm^2}}\right\}$	Radiation length [c] X_0 $\{\mathrm{g/cm^2}\}$	$\{\mathrm{cm}\}$	Density $\{\mathrm{g/cm^3}\}$ ($\{\mathrm{g}/\ell\}$ for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

Electromagnetic Cascades (I)

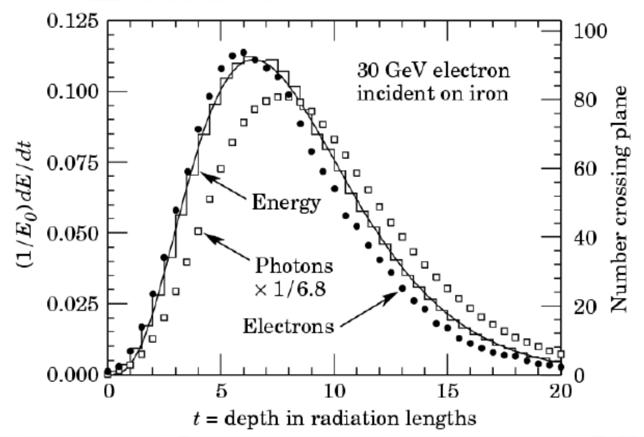
Starting from the first electron/photon electromagnetic shower (cascade) develops in thick materials:

Electron shower in lead.
7500 gauss
in cloud chamber.

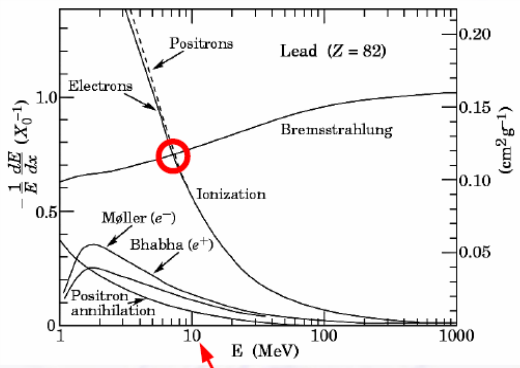
- **shower maximum (peak of energy deposition) slightly energy dependent**

$$t_{max}[X_0] = \ln\frac{E_0}{E_c}\,\frac{1}{\ln 2}$$

E_c = critical energy where energy loss (Ionization) = energy loss (Bremsstrahlung)



O (5 - 10 X_0)

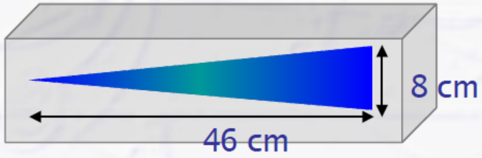


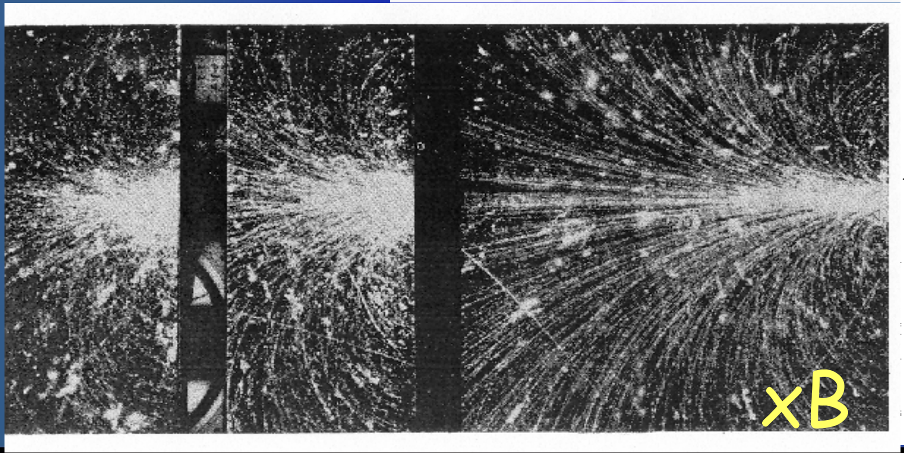
O (10 MeV)

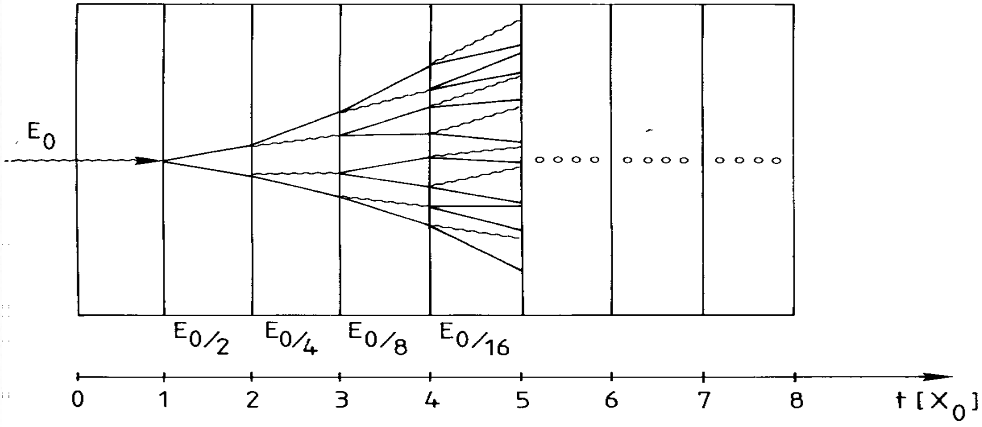
- **transversal shower width given by Moliere radius**

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

typically ~ 2 X_0

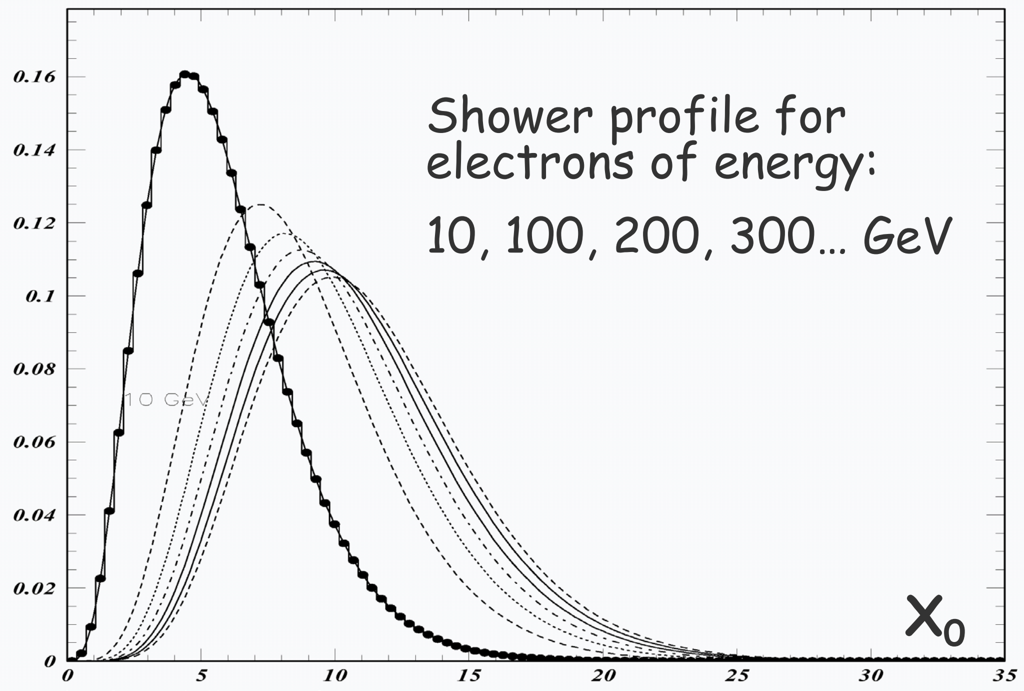






Electromagnetic Cascades (II)

Longitudinal profile



Transverse profile

- ✓ Multiple scattering for electrons
- ✓ Photons with energies in the region of minimal absorption travel away from shower axis

➔ *Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing 1X_0*

$$R_M = \frac{21\mathrm{MeV}}{E_C} X_0$$

$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} \left(Z >> 1\right)$$

Transverse shower containment:
75% E_0 within **1R_M, 95%** within **2R_M, 99%** within **3.5R_M**

➔ *Calorimeter granularity !*

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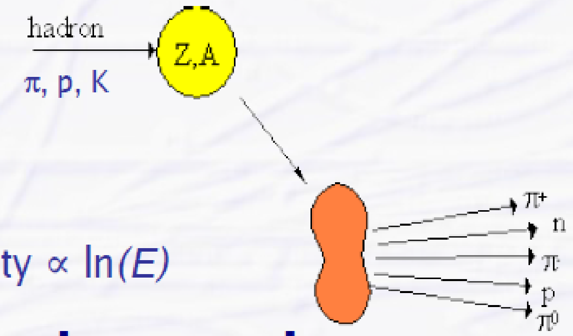
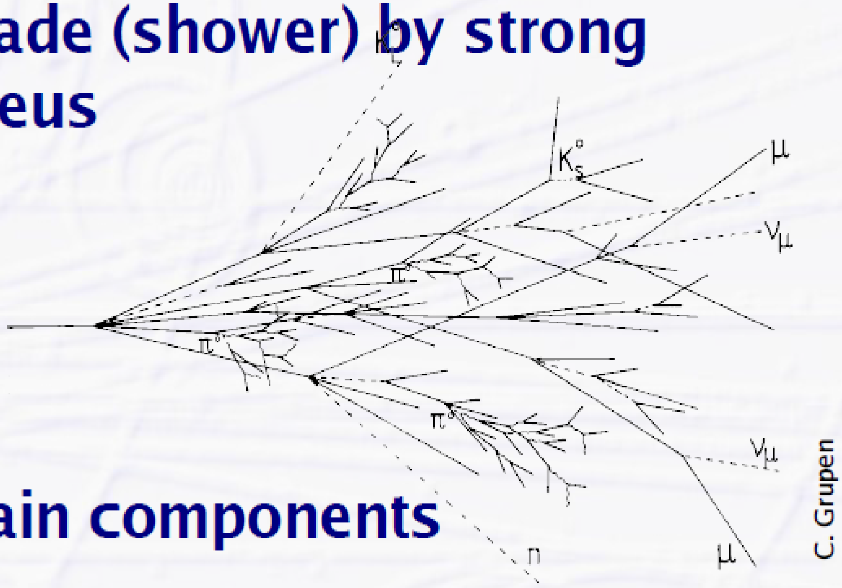
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—

Nuclear Interaction Length (λ_I)

- Similar as radiation length but important for hadrons
- Development of hadronic cascade (shower) by strong interaction of hadron with nucleus



multiplicity ∝ ln(E)



- Hadronic showers have two main components
  - hadronic
    - charged hadrons, breaking up of nuclei (binding energy) nuclear fragments, neutrons
  - electromagnetic (the unwanted part)
    - decay of neutral pions: $\pi^0 \rightarrow 2\gamma$ (100% branching ratio)

"Invisible" energy =
large energy fluctuations

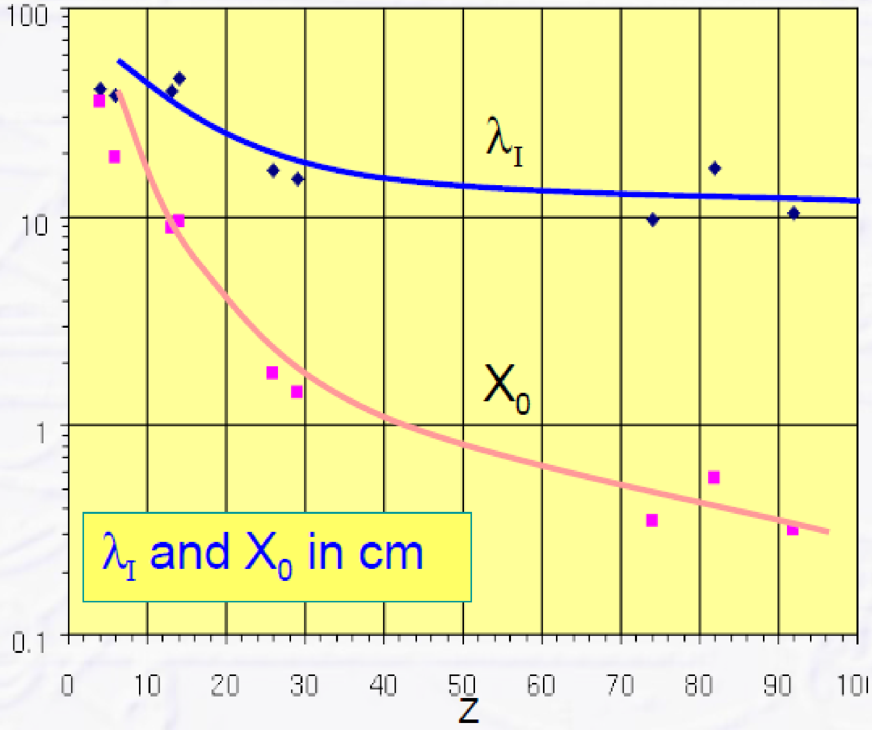
- Hadronic and EM energy component usually have different detector responses, e.g.
  - 100 GeV hadronic energy $\neq$ 100 GeV EM energy measured in detector

Radiation (X_0) and Nuclear Interaction Length (λ_I)

- **Typical radiation length**
  - gases, e.g. Argon ~100 m
  - light materials, e.g. Aluminum, Silicon ~10 cm
  - heavier metals, e.g. Iron, Copper, Lead ~ 0.5 – 1.5 cm

For $Z > 6$: $\lambda_I > X_0$

Material	Z	A	[g/cm^3]	X_0 [g/cm^2]	$_I$ [g/cm^2]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0



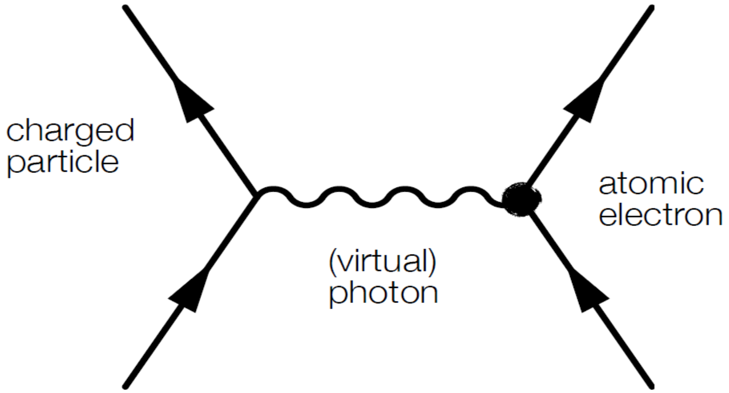
Energy Loss by Photon Emission

Instead of ionizing an atom or exciting the matter, under certain conditions the photon can also escape from the medium.

⇨ Emission of ***Cherenkov*** *and* ***Transition*** *radiation. This emission of real photons contributes also to the energy loss.*

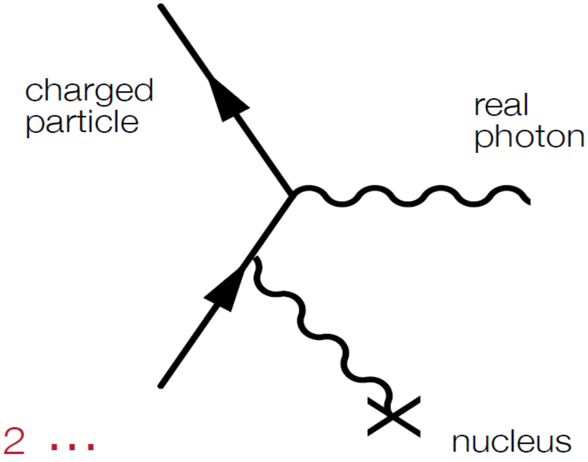
Interaction of charged particles with medium via

Electromagnetic interaction



Three possible processes:

Ionization (see above)
Cherenkov Radiation
Transition Radiation



For the derivation of the energy loss or the intensity of the emitted radiation consider …

Charged particle with velocity $v = \beta c$
Medium with dielectric constant $\varepsilon = \varepsilon_1 + i\varepsilon_2$ …

Represents/describes interaction of (virtual) photons with atoms of medium

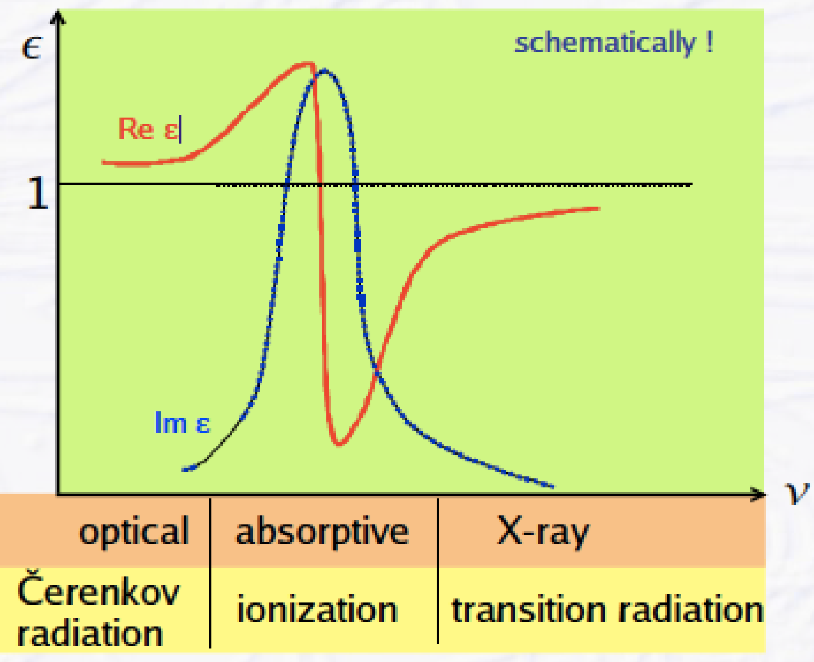
Energy Loss by Photon Emission

Ionization is one way of energy loss emission of photons is another...

Optical behavior of medium is characterized by the (complex) dielectric constant ***ε***

Re √ε = n Refractive index

Im ε = k Absorption parameter



optical	absorptive	X-ray
Čerenkov radiation	ionization	transition radiation

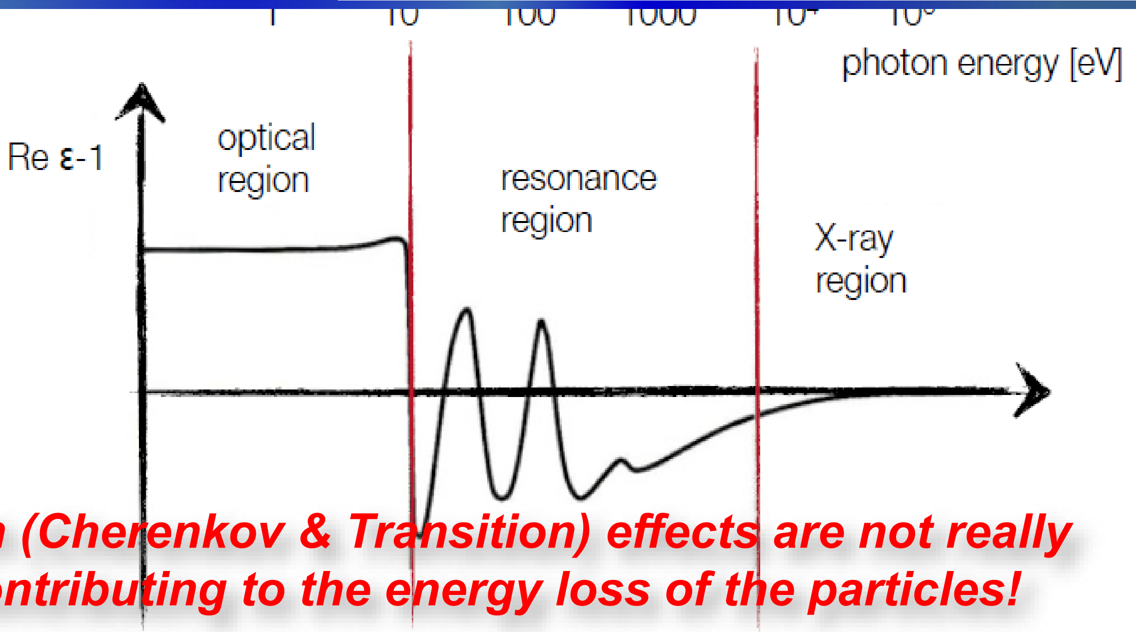
Imaginary part:

Photon absorption
[↦ absorption cross section]

Real part:

Refraction
[↦ modification of phase velocity]

$$u(\omega) = \frac{c}{\sqrt{\epsilon(\omega)}}$$



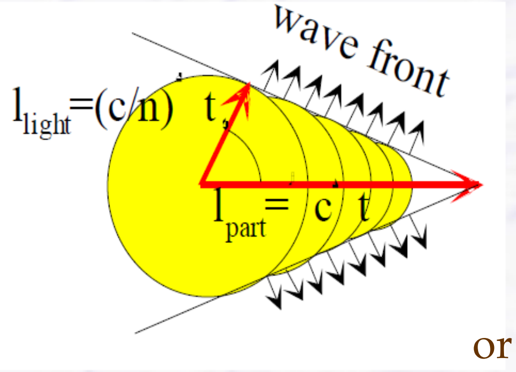
Both (Cherenkov & Transition) effects are not really contributing to the energy loss of the particles!

Cherenkov Radiation

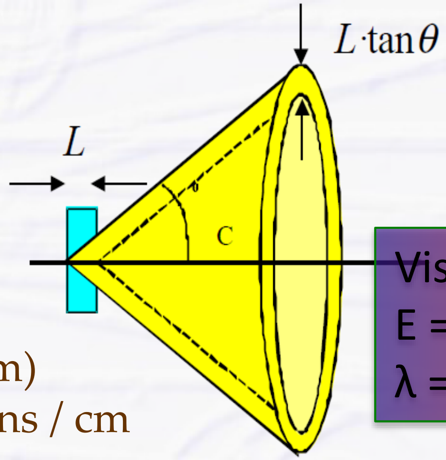
- **Čerenkov radiation is emitted when a charged particle passes though a dielectric medium with velocity** $\beta \geq \beta_{thres} = \frac{1}{n}$

speed of light in medium

→ classical picture: wave front or cone under Čerenkov angle



$$\cos\Theta_C = \frac{1}{n\beta}$$



Visible photons:
E = 1 - 5 eV;
λ = 300 - 600 nm

Typically O(1-2 keV / cm)
or O(200-1000) visible photons / cm

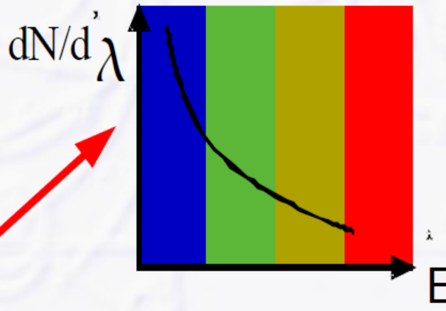
continuous wave front emission from track

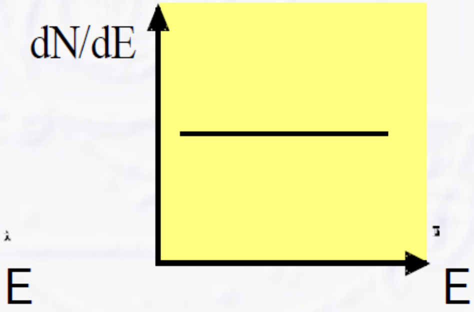
light cone emission when passing thin medium

→ number of emitted photons per unit length and unit wave length interval

$$\frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2} \qquad \frac{d^2N}{dx\,dE} = const$$

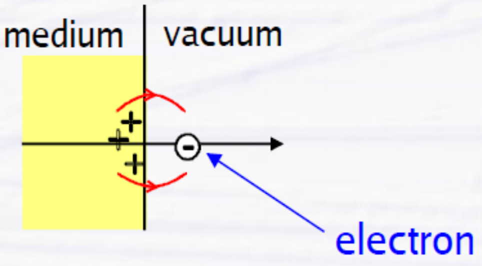
mainly UV photons!





Transition Radiation

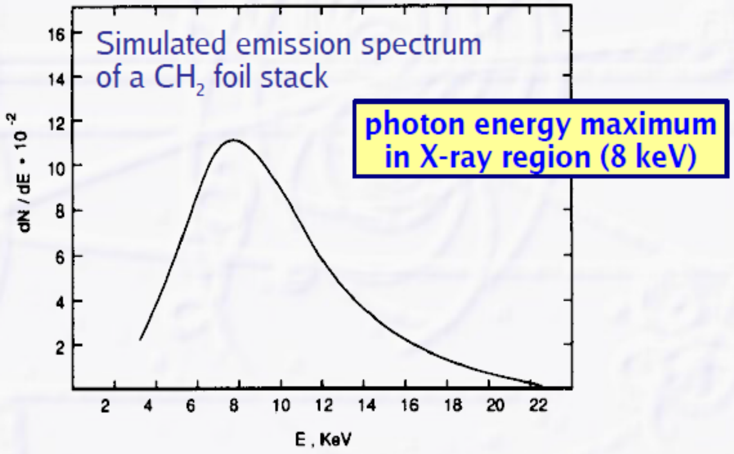
- **Predicted by Ginzburg and Franck in 1946**
  - emission of photons when a charged particle traverses through the boundary of two media with different refractive index
  - (very) simple picture
    - charged particle is polarizing medium
    - polarized medium is left behind when particle leaves media and enters unpolarized vacuum
    - formation of an electrical dipol with (transition) radiation



- **Radiated energy per boundary** $W \propto \gamma$
  - only very high energetic particles can radiate significant energy
    - need about $\gamma > 1000$
      - in our present energy range reachable with accelerators only electrons can radiate
      - but probability to emit photons still small

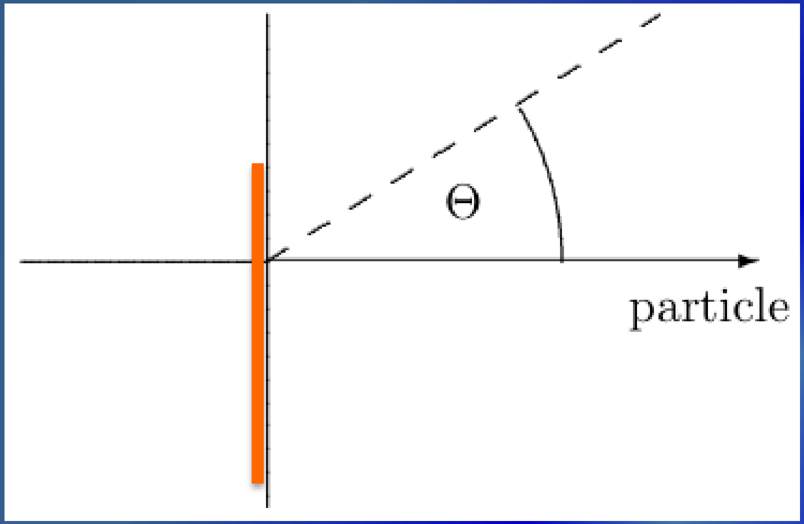
$$N_{photons} \propto \alpha_{EM} \approx \frac{1}{137}$$

need many boundaries (foils, foam) to get a few photons


Simulated emission spectrum of a CH_2 foil stack

photon energy maximum in X-ray region (8 keV)

Transition Radiation Detectors

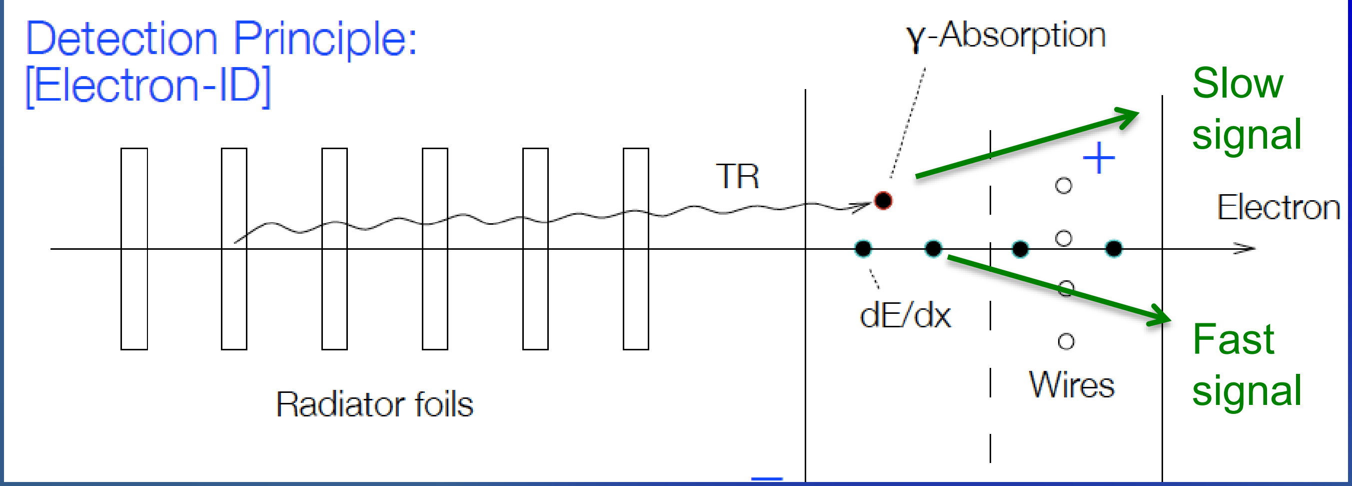


- *Typical emission angle:* $\Theta = 1/\gamma$
- *Energy of radiated photons:* $\sim \gamma$
- *Number of radiated photons:* az^2
- *Effective threshold:* $\gamma > 1000$

$$S = \frac{1}{3}\alpha z^2 \gamma \hbar\omega_P \quad (\hbar\omega_P \approx 20\text{eV})$$

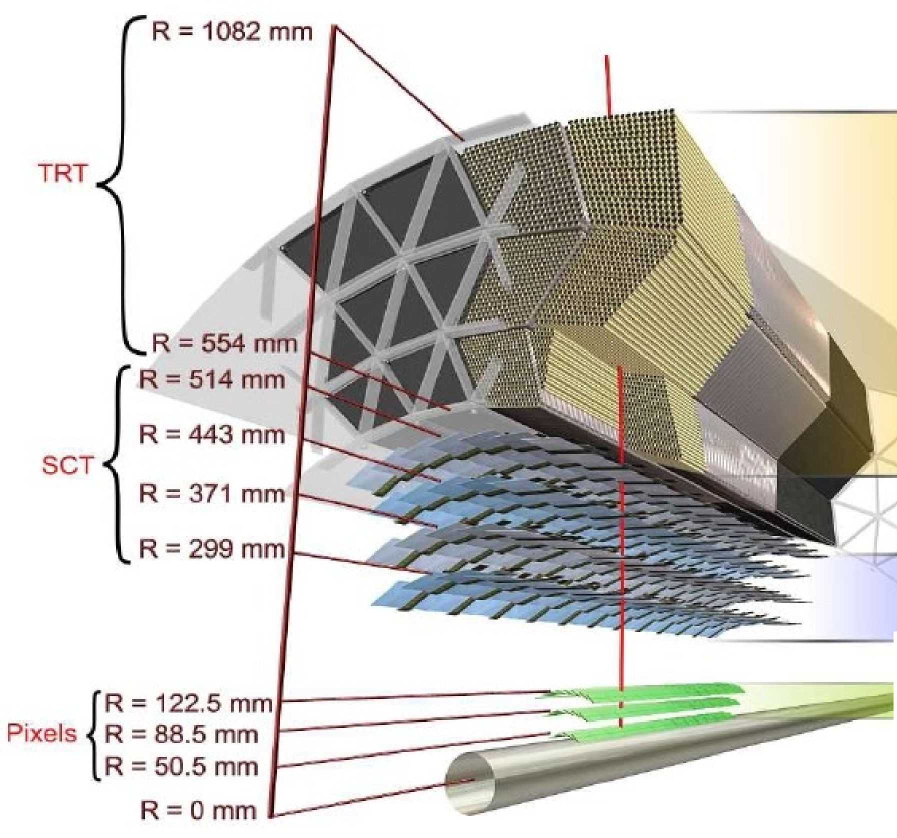
➔ *Use stacked assemblies of* ***low Z material with many transitions***

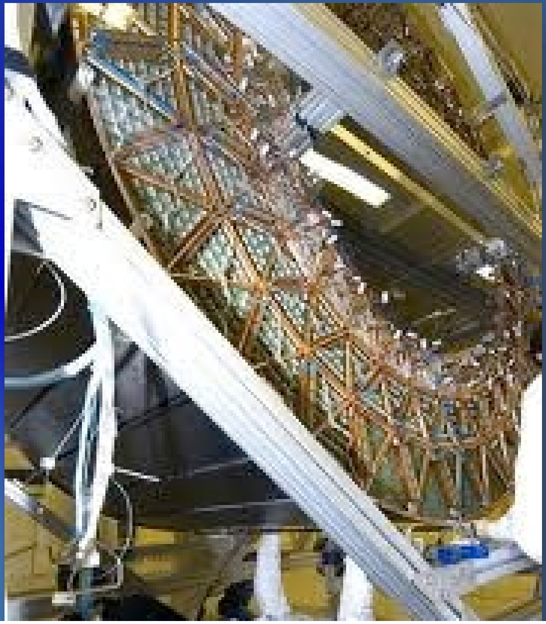
+ ***a detector with high Z gas***

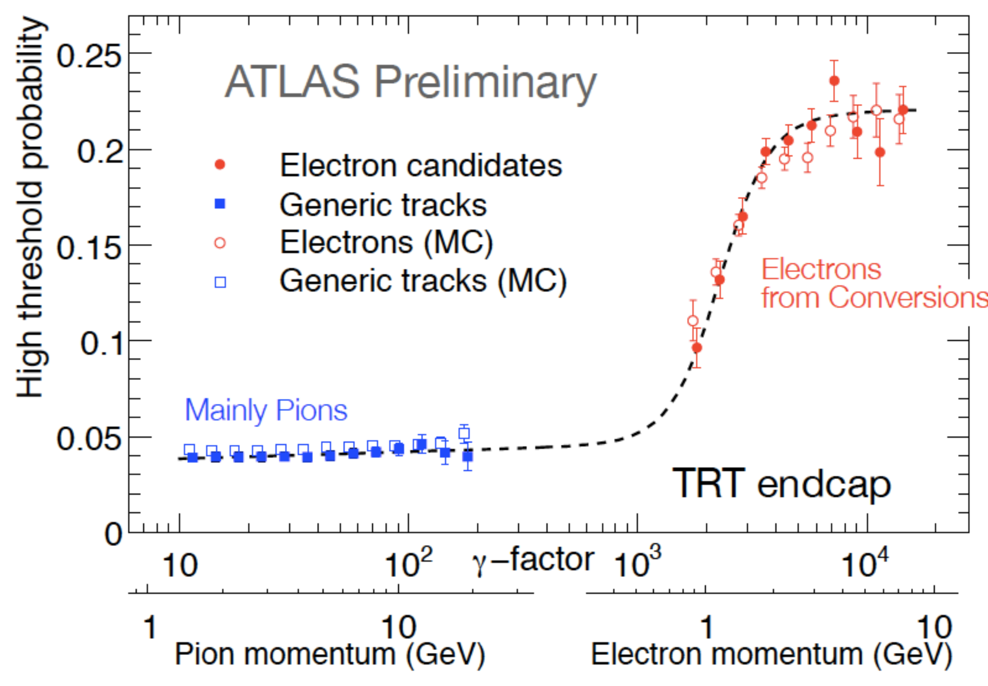


Note: Only X-ray (E>20keV) photons can traverse the many radiators without being absorbed

Transition Radiation Detectors







Example: ATLAS Transition Radiation Tracker (TRT)

- *straw tubes with xenon-based gas mixture*
- *4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire*

Neutron Interactions with Matter

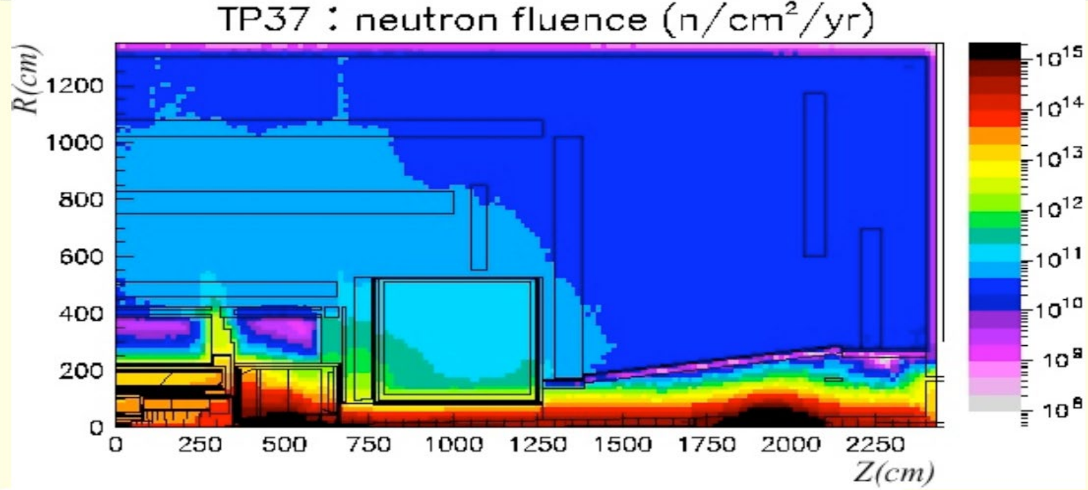
Neutron has no charge, can be detected only through charged particle produced in (weak or) strong interaction **=> short range => very penetrating**

- *Conversion and elastic scattering for E < 1 GeV. For instance*
  - *$n + {}^{6}Li \rightarrow \alpha + {}^{3}H$, $n + {}^{3}He \rightarrow p + {}^{3}H$ E < 20 MeV*
  - *$n + p \rightarrow n + p$ E < 1 GeV*
- *Hadronic cascade for E > 1 GeV*

- *Neutrons can travel sometimes for more than 1 μs in detectors*

  → **outside electronics readout window …**

- *A lot of low energy neutrons produced in LHC experiments Interactions in the whole cavern*
- *(e.g. ATLAS experiment)…*



At r=11 cm, photons flux of 30 MRad !
100 Rad ~ 6.2410^{12} MeV/kg deposited energy (1J/kg)

Neutrino Interactions with Matter

- *Only weak interaction*

- *$v + n \rightarrow l^- + p$ or anti $v + p \rightarrow l^+ + n$ ➔ detect the charged lepton and the nucleon recoil*

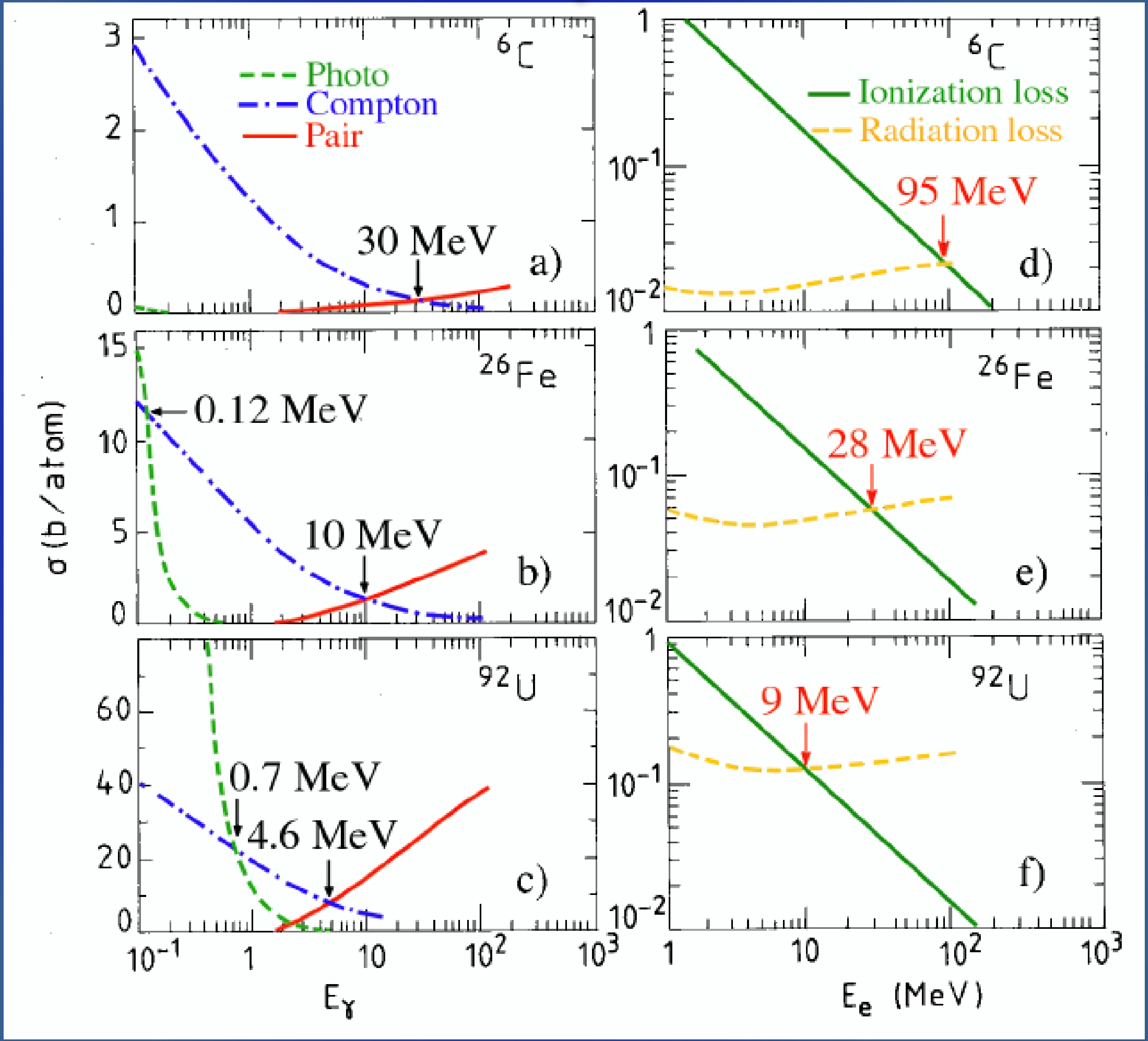
- *Detection efficiency in ~1 m iron about 6.10^{-17}…*
- *Whatever technological improvement, neutrinos detector can only be huge detector*

- *In collider experiment, indirect detection :*
  - *"Fully" hermetic detector (!)*
  - *Sum all visible energy/momentum*
  - *Use beam energy constraint → neutrino(s) are taking the missing energy/momentum*

Material Dependence

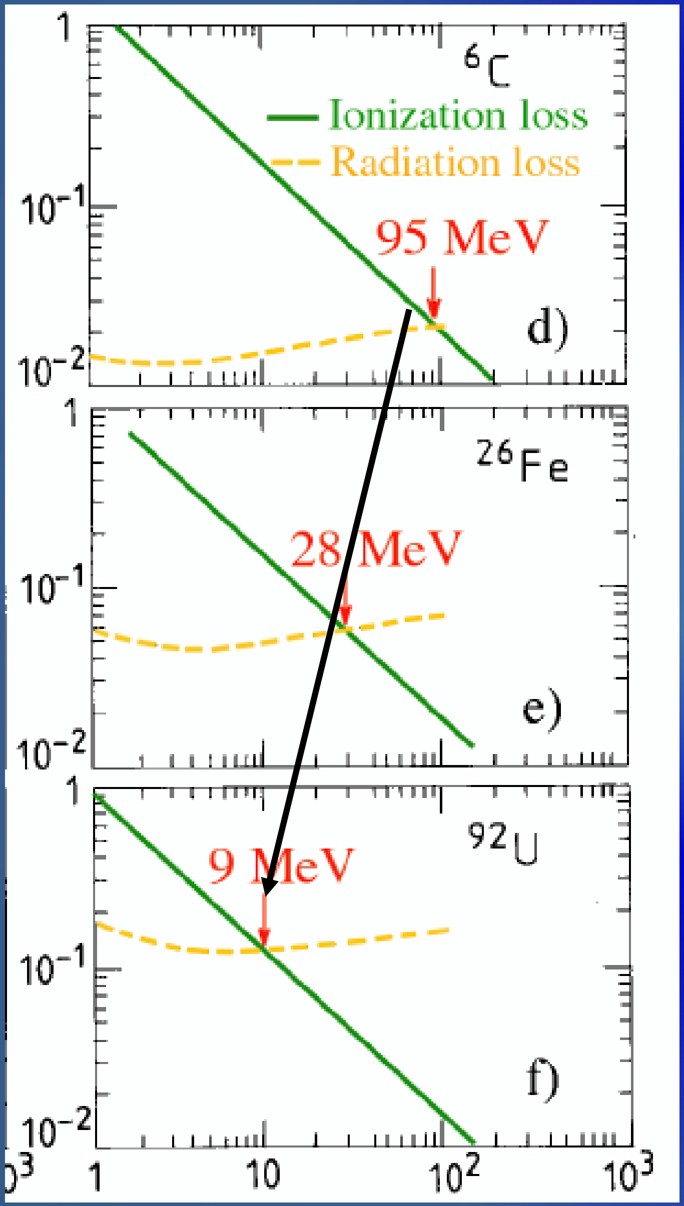
Increasing Z

Gammas



Electrons

Summary of Interactions of ELECTRONS with Matter



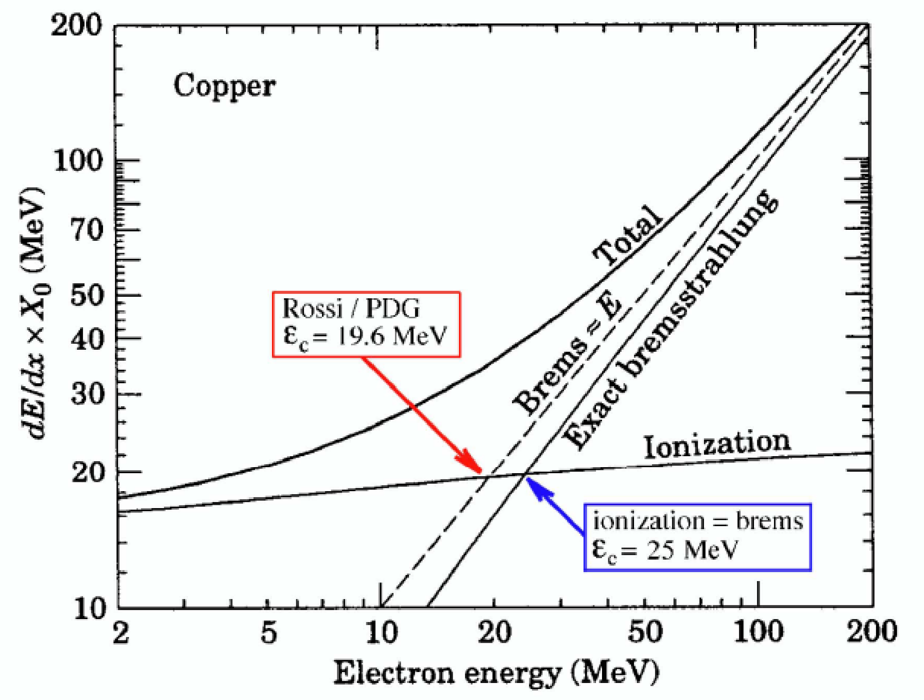
↓ *Increasing Z*

In high Z materials
particle multiplication
at lower energies

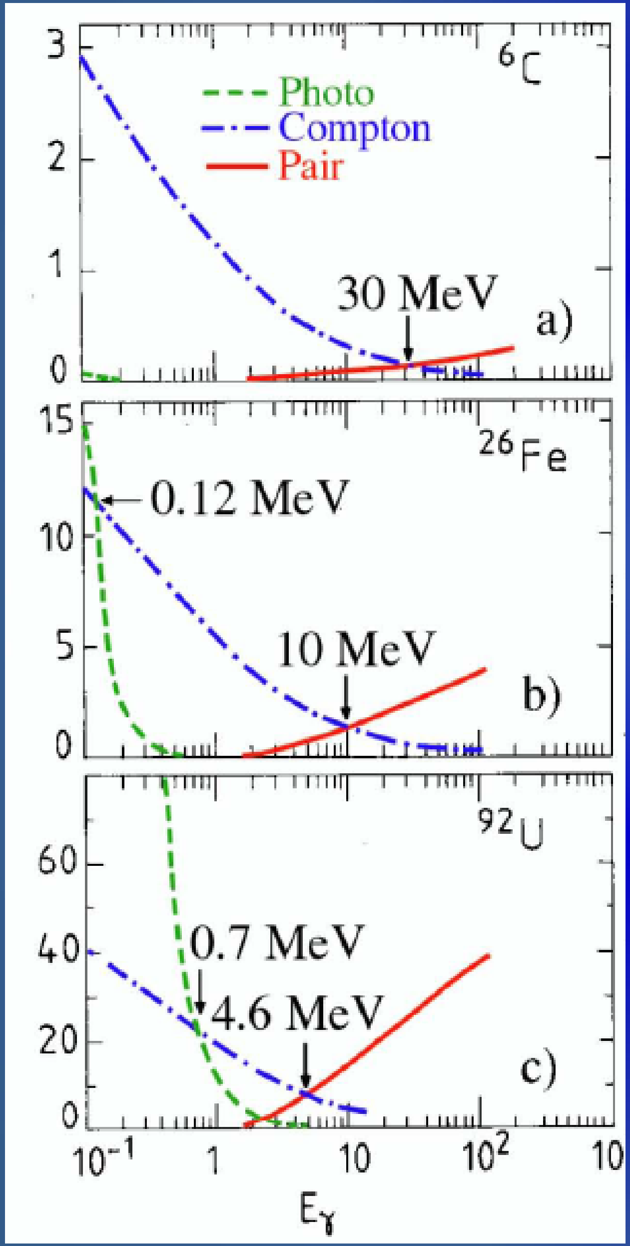
- *Electrons* lose energy by: *ionization* *radiation*

Critical energy ϵ_c: $\frac{dE}{dx}$ (ion) $=$ $\frac{dE}{dx}$ (rad)

$\epsilon_c \propto 1/Z$ PDG: $\epsilon_c = 610\ \text{MeV}/(Z+1.24)$



Summary of Interactions of PHOTONS with Matter



⬇ **Increasing Z**

- *Photons* interact by:

1) *Photoelectric* effect $\sigma \propto Z^5,\ E^{-3}$

2) *Compton* scattering $\sigma \propto Z,\ E^{-1}$

3) *Conversion* into e^+e^- σ increases with E, Z, asymptotic at $\sim$ 1 GeV

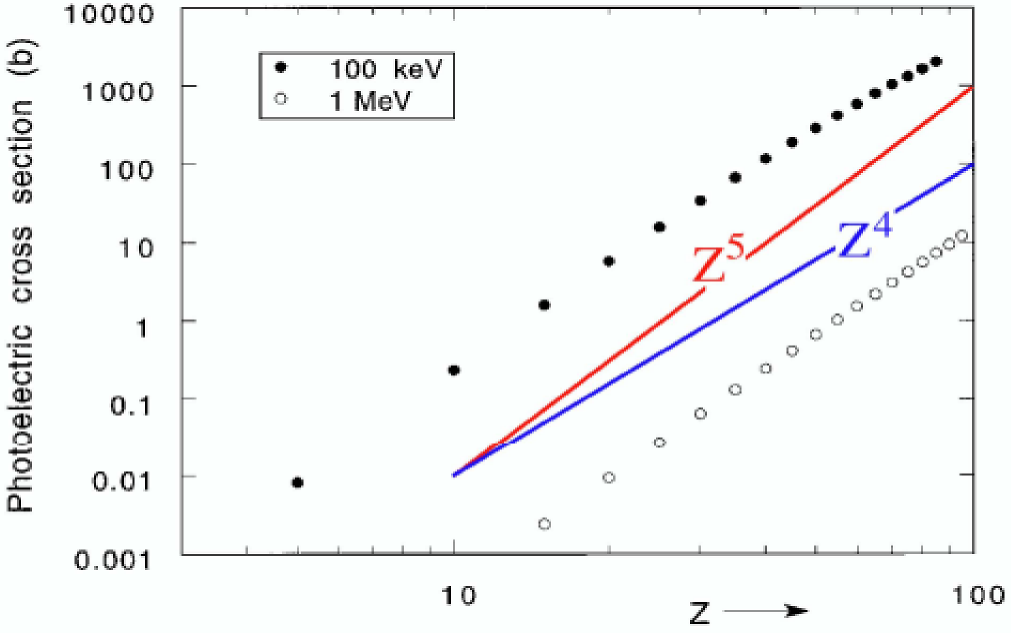
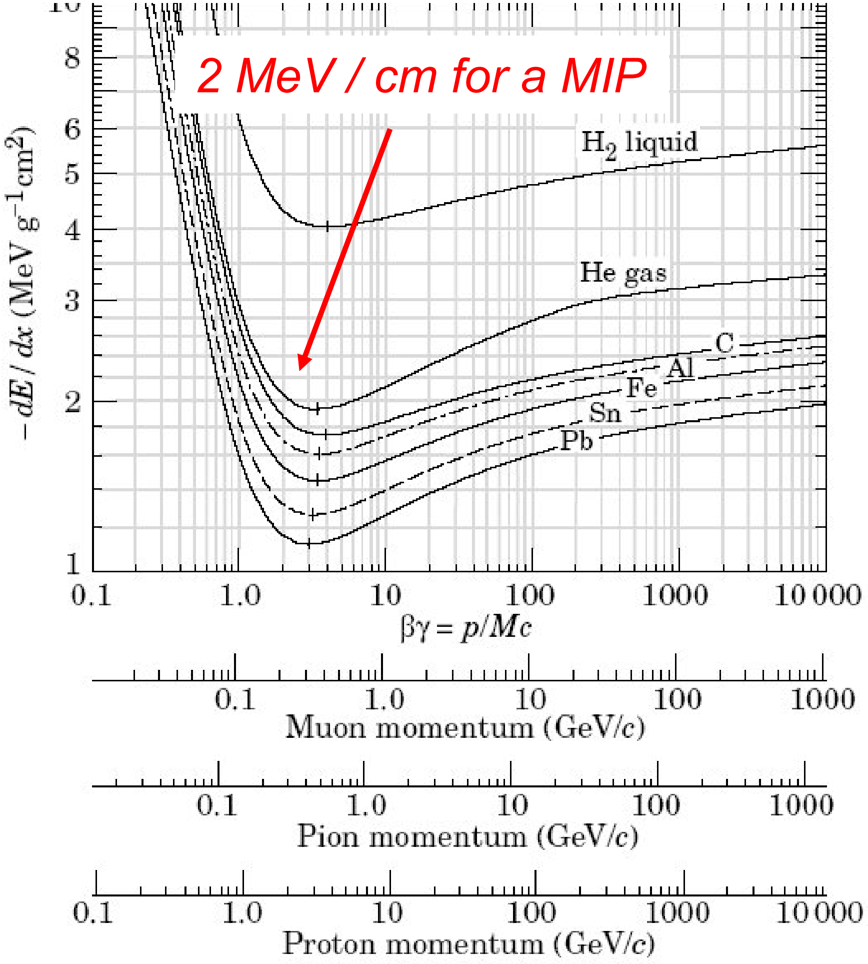


FIG. 2.3. Cross section for the photoelectric effect as a function of the Z value of the absorber. Data for 100 keV and 1 MeV γs.

Summary of Interactions of Particles with Matter

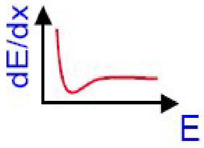
Bethe-Bloch for heavy charged particles



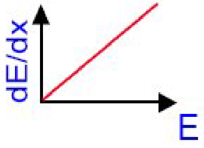
Radiation length X_0

e^+ / e^-

- Ionisation

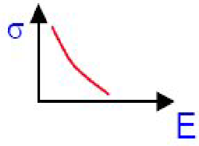


- Bremsstrahlung

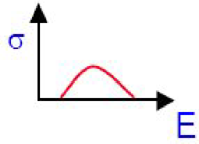


γ

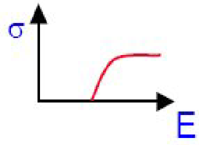
- Photoelectric effect



- Compton effect



- Pair production



Interaction of hadrons : many different particles produced,

interaction length λ_I