დეტექტორები

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- ☐ **<u>Passage of particles through matter</u>**
- ☐ **Photon detectors**
- ☐ **Scintillators**
- ☐ **Cherenkov light detectors, time-of-flight detectors**
- ☐ **Calorimeters**
- ☐ Not covered : Tracking detectors

ქუთაისი, 1-3/11/2024

❑ *Wanted: particle ID (mass, charge) and particle kinematics (momentum, energy)*

$$E^2 = p^2 c^2 + m_0^2 c^4$$

energy E :   measured in **eV**

momentum p :   measured in eV/c or **eV**

mass m_0 :   measured in eV/c^2 or **eV**

$$\beta = \frac{v}{c} \qquad (0 \le \beta < 1) \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad (1 \le \gamma < \infty)$$

$$E = m_0 \gamma c^2 \qquad p = m_0 \gamma \beta c \qquad \beta = \frac{pc}{E}$$

1 eV is a small energy.

1 eV $= 1.6 \cdot 10^{-19}$ J

m_{bee} = 1g $= 5.8 \cdot 10^{32}$ eV

v_{bee} = 1 m/s => E_{bee} = 10^{-3} J = $6.25 \cdot 10^{15}$ eV

E_{LHC} = 14 · 10^{12} eV

However,
LHC has a total stored beam energy
10^{14} protons x 14 · 10^{12} eV ~ 10^8 J

or, if you like,
     one 100 T truck
       at 100 km/h

TIR

HOW'S MY
DRIVING?
NOT THAT
GIVE

Berkin

Some units and conventions

Cross section σ or the differential cross section dσ/dΩ is an expression of the probability of interactions.

Beam spot area A_1

Beam spot area A_2

$F_1 = N_1/t$

$F_2 = N_2/t$
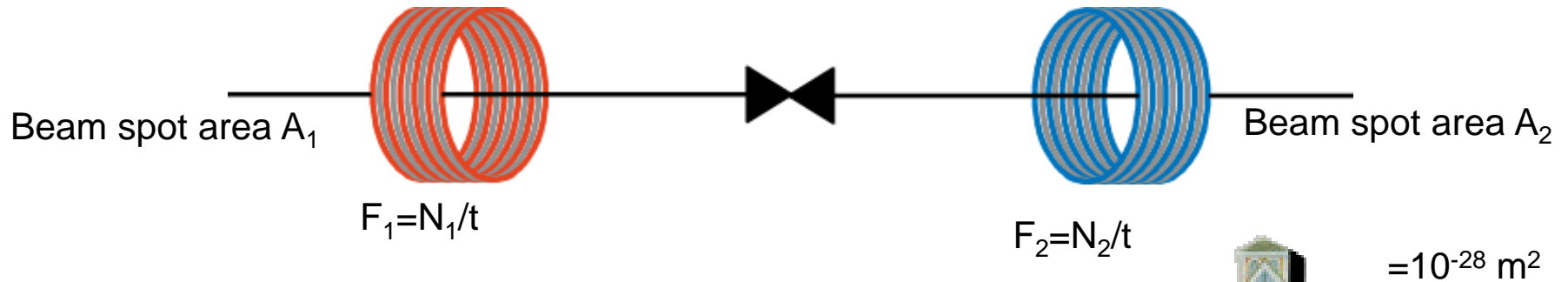
$= 10^{-28}$ m^2

The interaction rate, R_{int}, is then given as:

$$R_{int} \propto \frac{N_1 N_2}{A \cdot t}$$

$$= \sigma \mathcal{L}$$

σ has the dimension area.
1 barn = 10^{-24} cm^2 = 10^{-28} m^2

The luminosity, $\mathcal{L}$ is given in cm^{-2}s^{-1}

The integrated luminosity, $\int \mathcal{L} \, dt$, is given in barn^{-1}

Grant Wood, Fruits of Iowa: Boy Milking Cow, 1932

from C. Joram, SSL 2003

❑ At early LHC in 100 days of operation per year: $\int \mathcal{L} \, dt$ ~ 10 fb^{-1} for $\mathcal{L}$ ~ 10^{33} cm^{-2}s^{-1}

❑ Next e$^+$e$^-$ machines ➔ few 10 x ab^{-1}

To reach unexplored area
of HEP:

$\Longrightarrow$ Increase Energy

$\Longrightarrow$ Increase Luminosity

} Accelerators

$\Longrightarrow$ Increase Precision

{ Theory & Analysis

Detectors

The CERN accelerator complex

The CERN accelerator complex
Complexe des accélérateurs du CERN

LHC: 6.8 TeV
SPS: 450 GeV
PS booster: 2 GeV
PS: 26 GeV
LINAC 4: 160 MeV

CMS

North Area
Neutrino Platform 2013

LHC 2010 (27 km)

ALICE

LHCb

TT20

SPS 1976 (7 km)

TT40   TT41   TT42

AWAKE 2016

TI8

ATLAS

TI2

HiRadMat 2011

TT66

TT60

AD 1999 (182 m)   ELENA 2020 (31 m)

MEDICIS 2010

ISOLDE 1992

BOOSTER 1972 (157 m)

RIBs

REX/HIE-ISOLDE 2001/2015

East Area

TT10

p̄   p

n_TOF 2001

TT2

H⁻   p

PS 1959 (628 m)

n   p

LINAC 4 H⁻ 2020

LINAC 3 Ions 1994

LEIR 2005 (78 m)

CLEAR 2017

e⁻

▶ H⁻ (hydrogen anions)   ▶ p (protons)   ▶ ions   ▶ RIBs (Radioactive Ion Beams)   ▶ n (neutrons)   ▶ p̄ (antiprotons)   ▶ e⁻ (electrons)   ▶ μ (muons)
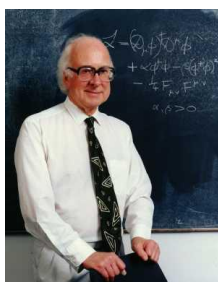
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear
Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive
EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator //
n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

CMS
# A Compact Solenoidal Detector for LHC

FORWARD CALORIMETER

MUON CHAMBERS

TRACKER

CRYSTAL ECAL

HCAL

SUPERCONDUCTING COIL

RETURN YOKE

Y
Z
X

Total weight   : 12,500t.
Overall diameter : 15.00m
Overall length   : 21.60m
Magnetic field   : 4 Tesla

CMS-PARA-OO1-11/O7/97   JLB.PP
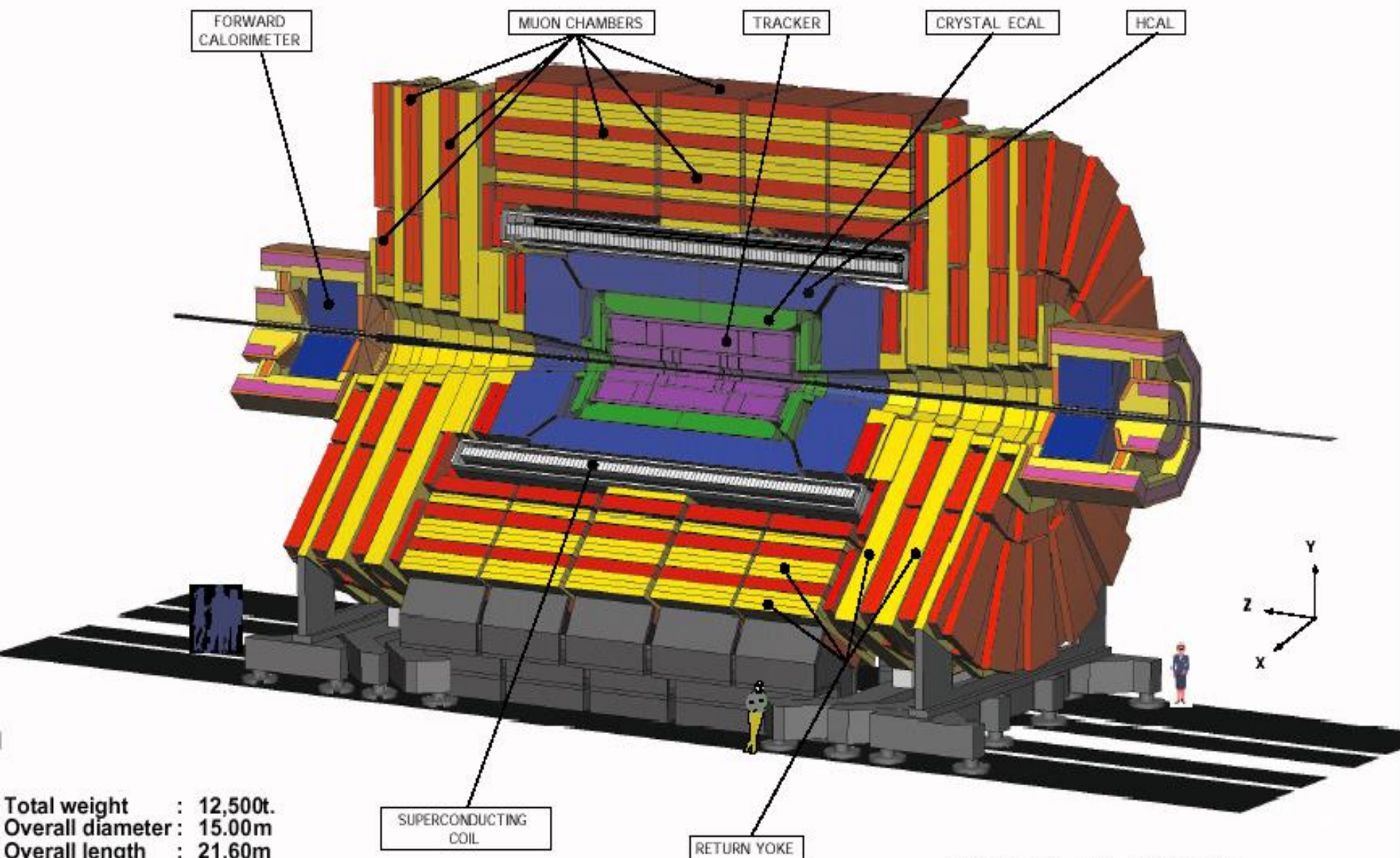
Discovery of boson
with ATLAS and CMS

- **Inelastic: 10^9 Hz**

- **Higgs (100 GeV/c^2): 0.1 Hz**

- **Higgs (600 GeV/c^2): 10^{-2} Hz**

- Selection : $1:10^{10-11}$

- Operate in high radiation environment

- Resolve MANY superimposed events per BX

- High granularity detectors

- Fast electronics/detectors (25 ns)

Energy scale crucial
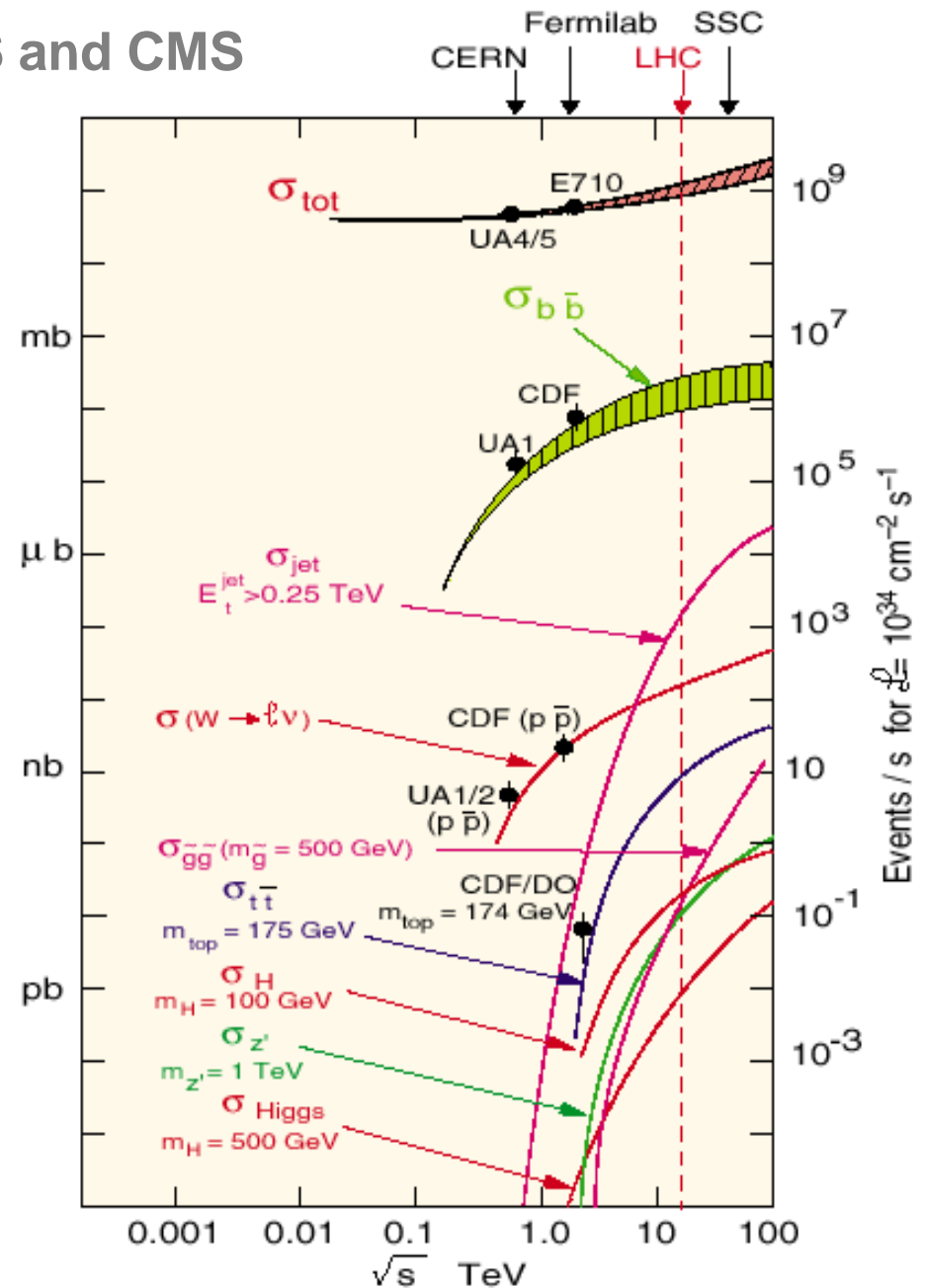
What can we measure/register ?

Measure stable and quasi-stable particles (e, γ, μ, π, K, p, n, ν) :

Kinematics (momentum and/or energy)

The way particle interacts with / passes through detectors

All other particles reconstructed via their decays to (quasi-) stable particles :

Invariant mass of the system of daughter particles

+ Decay vertex separated from production vertex for some particles decaying via weak interaction

Main goal of instrumentation for HEP :

Precisely/fast **measure kinematics** of (quasi-) stable particles

Unambiguously/fast **identify** them

For that :

We study **how particles interact with the matter**

and

We choose the **detector technologies** that match the physics tasks

General statements

➔ Any device that is to detect a particle must interact with it in some way.

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

(Heavy) charged particle interaction with matter

Energy (kinetic) loss by Coulomb interaction with the atoms/electrons :

❑ Excitation : the atom (or molecule) is excited to a higher level

atom* → atom + γ

low energy photons of de-excitation

➔ light detection

❑ Ionization : the electron is ejected from the atom

electron / ion pair

➔ charge detection

❑ Instead of ionization/excitation real photon can be produced under certain conditions

➔ Cherenkov or Transition radiation

Contribute very little to the energy loss (< 5%),

can be neglected but they are used for particle ID

Bethe-Bloch:

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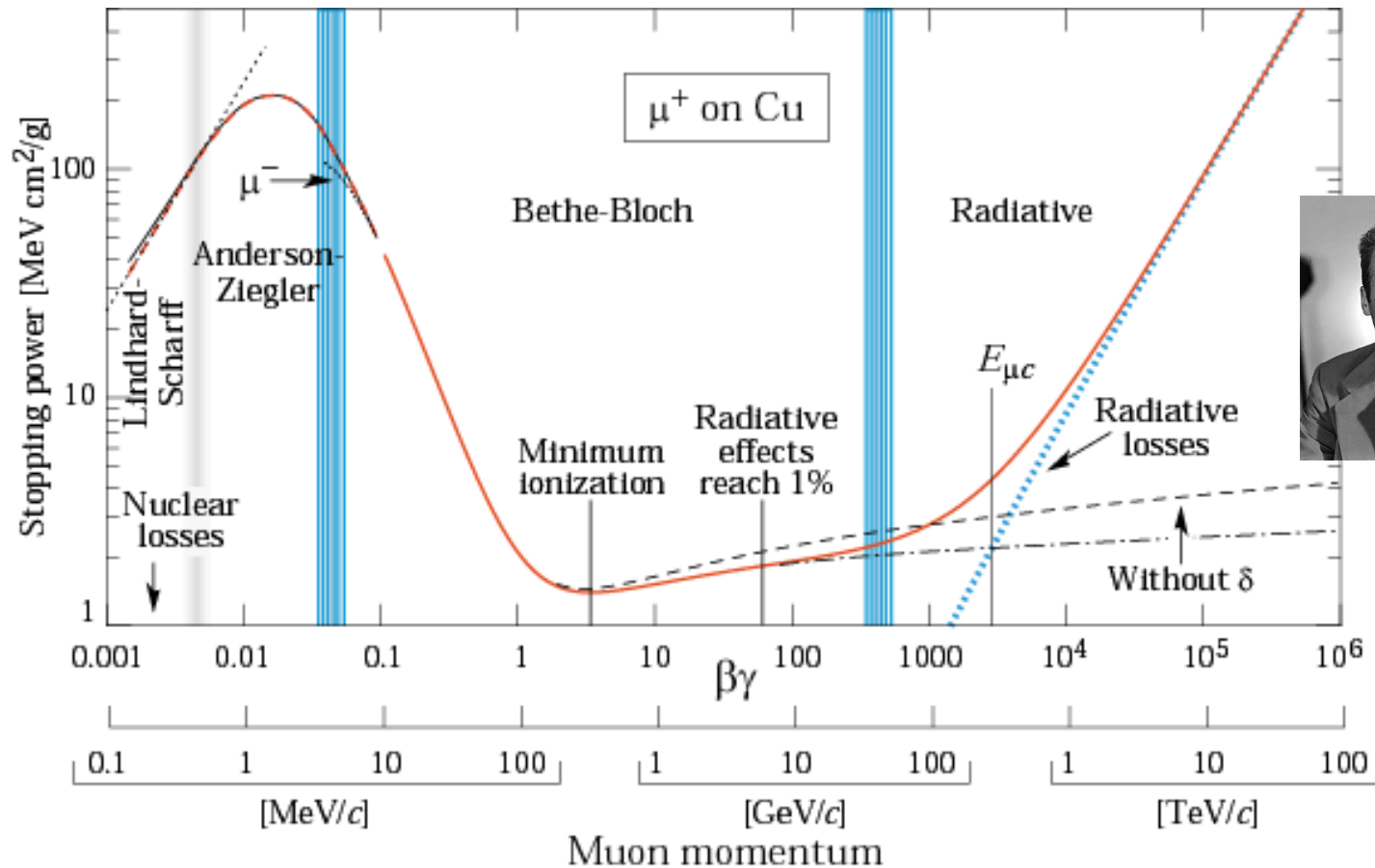
-2 C/Z
(shell correction)

μ⁺ on Cu

Stopping power (**-<dE/dx>**) for positive muons in copper as a function of
βγ = *p/Mc* over nine orders of magnitude in momentum (12 orders of magnitude
in kinetic energy). Solid curves indicate the total stopping power.

$$K = -4\pi N_A r_e^2 m_e c^2 \approx 0.307 MeV.g^{-1}.cm^2$$

Maximum kinetic energy that can be imparted to a free electron in a single collision :

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

I : Ionization constant or mean excitation potential, takes into account properties of electronic orbitals. Theoretical calculation seems quite complex and not done for many elements

➔ semi-empirical approach

Good approximation

$$\begin{cases} Z < 16 \rightarrow \dfrac{I}{Z^{0.9}} \approx 16eV \\ Z > 16 \rightarrow \dfrac{I}{Z} \approx 10eV \end{cases}$$

I/Z~10 eV

ICRU 37 (1984)

Barkas & Berger 1964
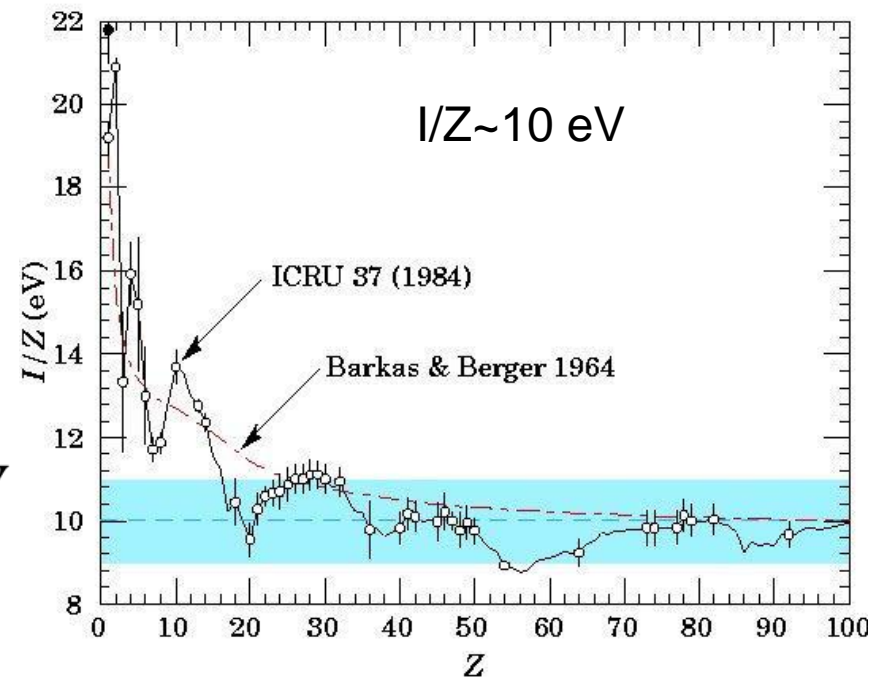
Bethe-Bloch with corrections yields few % accuracy for energy losses in Cu like material for the "Bethe-Bloch" region

Bethe-Bloch at Low energy :

❑ C/Z : shell correction to account for atomic binding. At low energy
the incident particles have less chance to interact with the electronic inner
orbits. For copper ~1% at βγ=0.3

❑ 0.01 < β < 0.05 : phenomenological fitting, Andersen and Ziegler

❑ β < 0.01 ("velocity" of outer atomic electrons) :
                            electronic stopping power ~ β, Lindhard

❑ at very low energy (e.g. < 100 eV protons) : non-ionizing energy loss
                                    dominates

❑ Bethe-Bloch with corrections ➔ precise at ~1% level
                                down to β~0.05 (~1 MeV for protons)

Bethe-Bloch at High energy: density effect

❑ At high energies, the electric field extends, and distant-collision contribution increases as lnβγ

❑ Relativistic rise ~2lnβγ

❑ δ(βγ)/2 : charge density effect correction, comes from polarization of the atoms along incoming particle => screening effect of the field, decreases loss at high energy.

At very high energies:
δ/2 -> ln($\hbar\omega_p$/I)+lnβγ-1/2
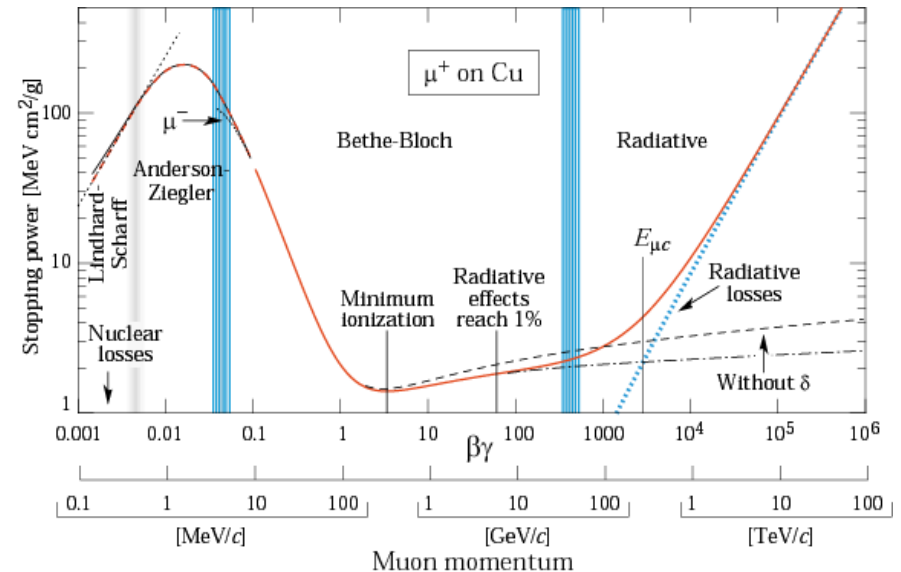
Bethe-Bloch at High energy: density effect

At very high energies:

$\delta/2 \rightarrow \ln(\hbar\omega_p/I) + \ln\beta\gamma - 1/2$

Remaining relativistic rise from the $\beta^2\gamma$ growth of T_{max}, due to (rare) large energy transfers to a few electrons

When these events are excluded
➔ Fermi plateau
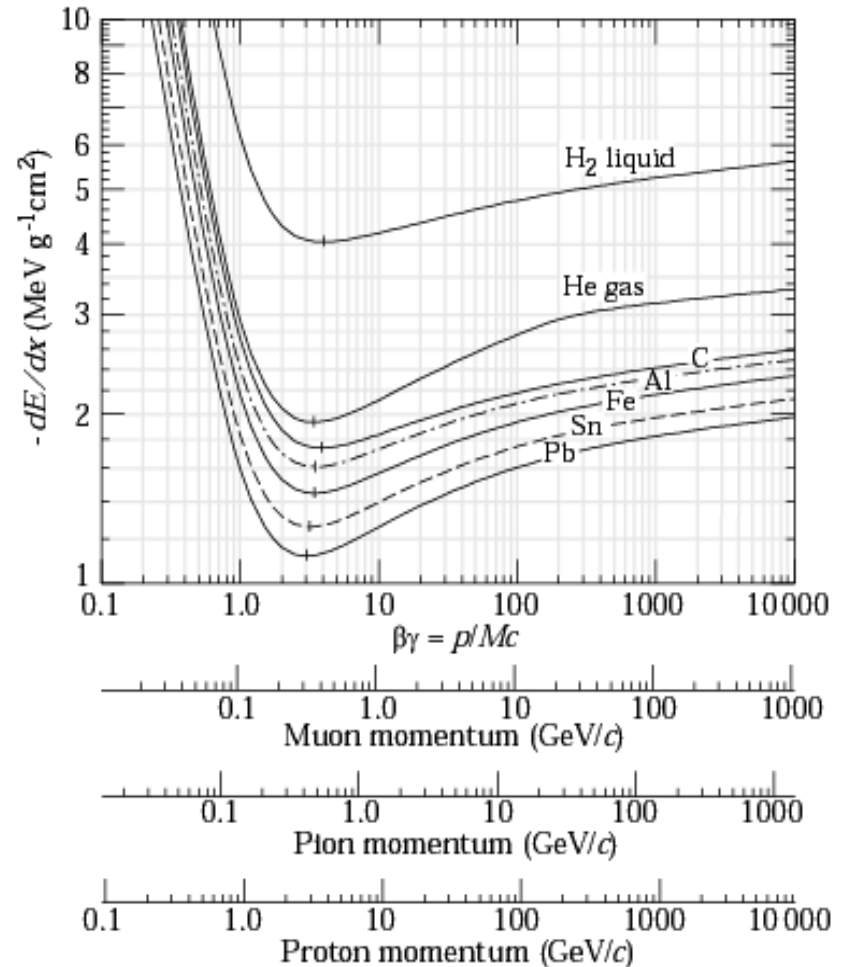
Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.
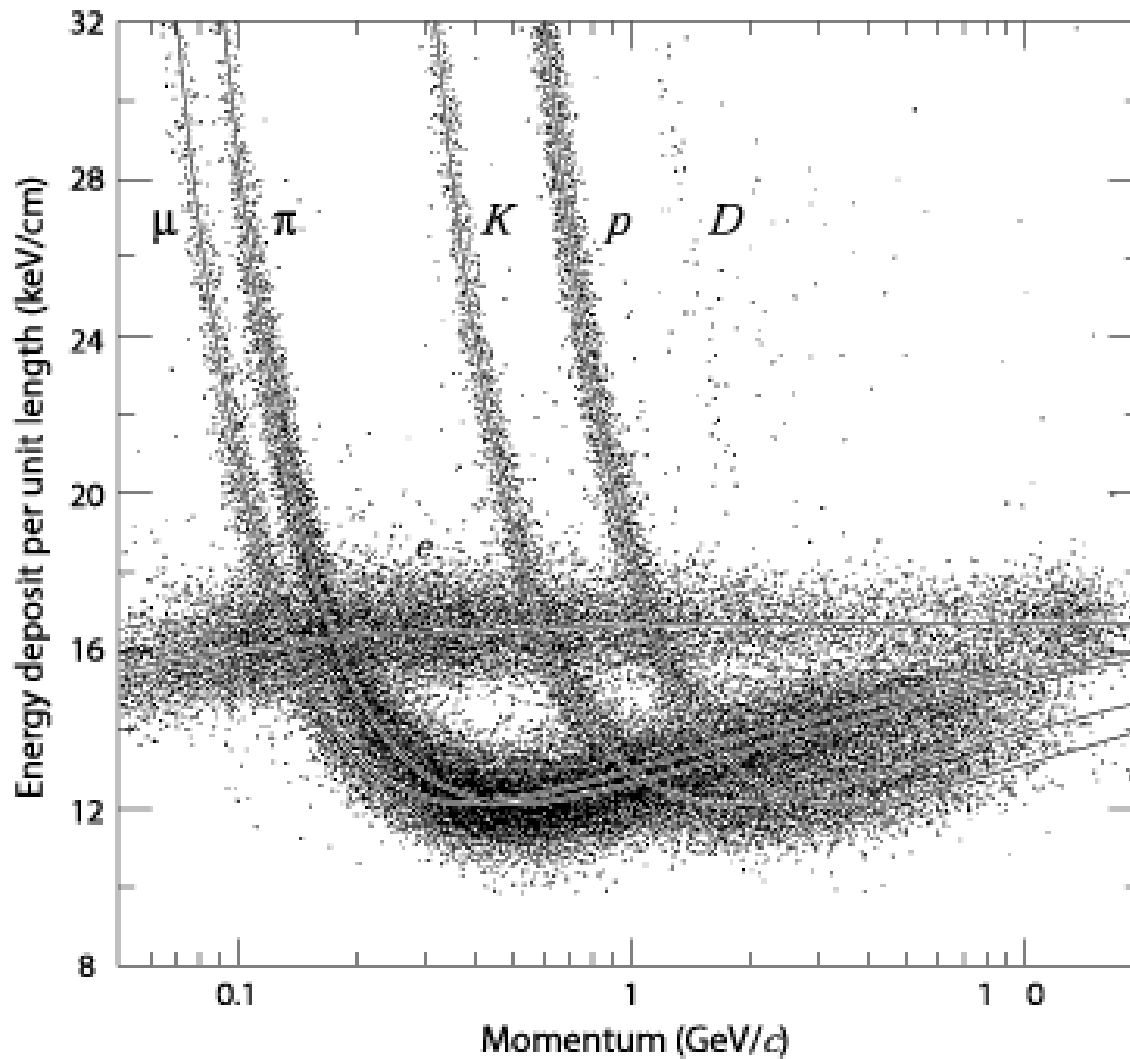
Minimum Ionizing Particle :
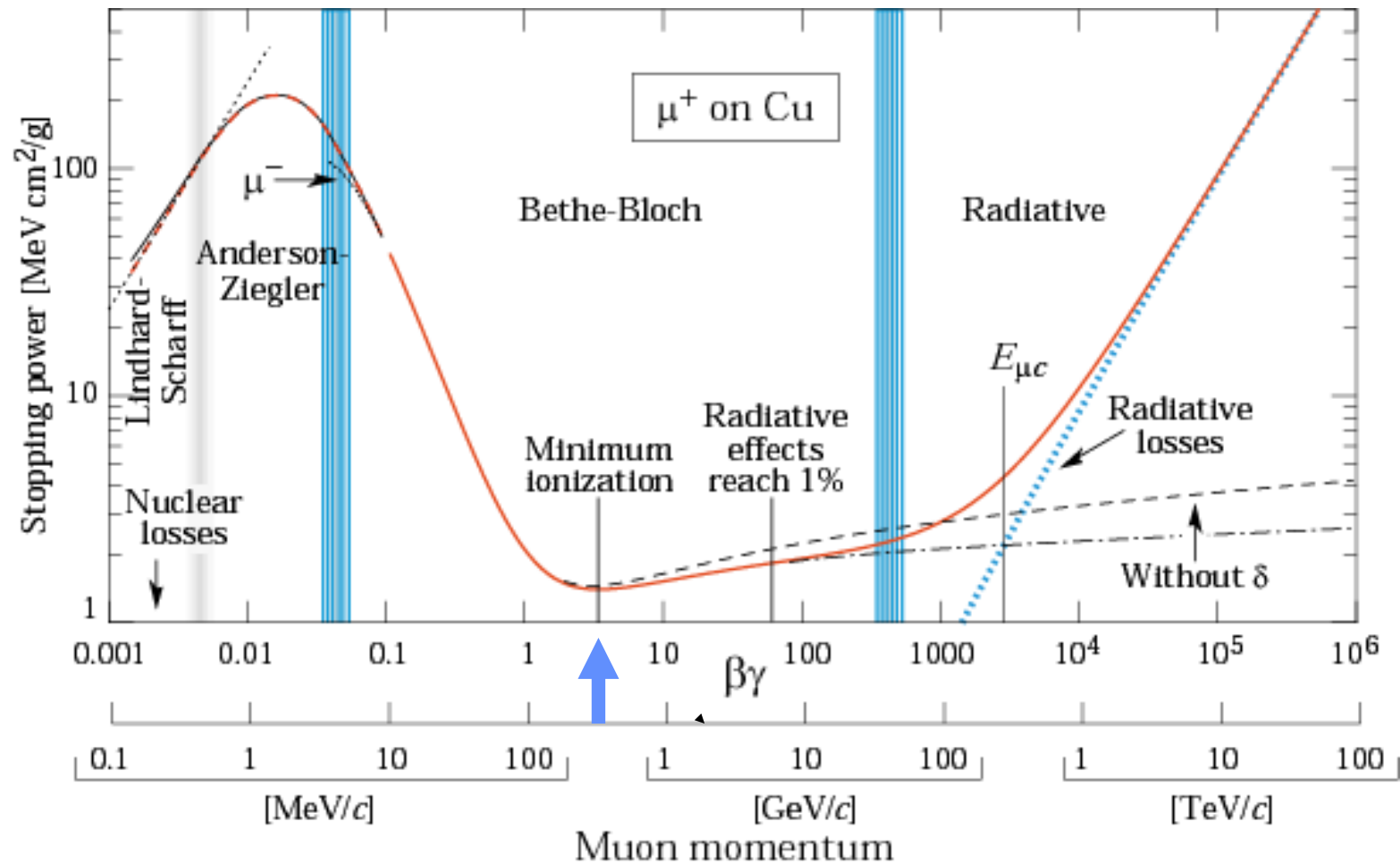
The minimum is approximately independent of the material

❑ Minimum at $\beta\gamma \sim 3 \dots 4$

❑ Similar for all elements
  ~2 MeV/(g/cm^2)
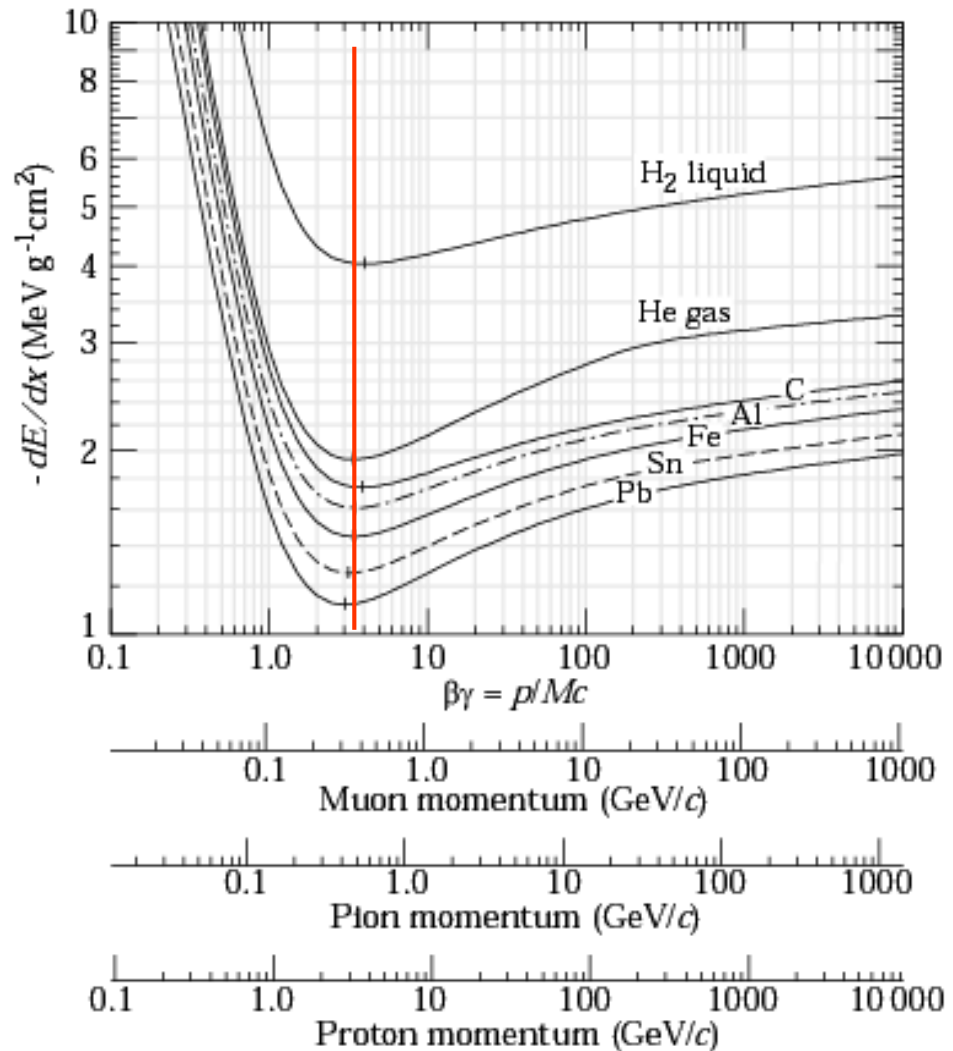
Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.

Ar-CH4 80:20, 8.5 atm, 185 samples

Particle ID relying on dE/dx depends on p (and δp) and particle_hypothesis_1,2

Bethe Bloch describes the average energy loss. For moderate thickness absorber fluctuations on this energy loss described by a Landau distribution.
For thin absorber (small dx) fluctuations become large

The energy loss is larger at small E, i.e. end of the path in matter

➔ Bragg peak

Fundamental for medical application, hadron therapy

Depth in water (cm)
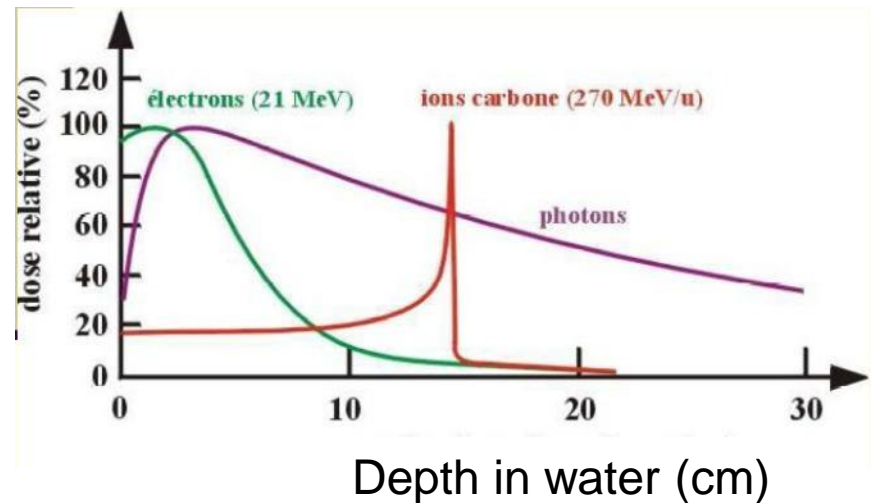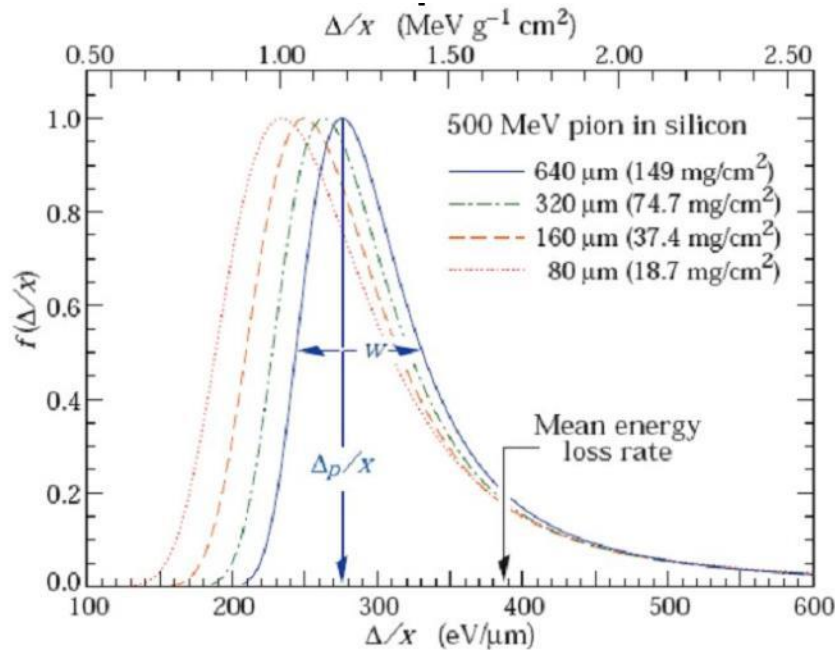
Energy loss of a 10 GeV muon in 1 cm of plastic scintillator (γ = 1) or a gas chamber (γ = 0.001) ?

Muons can be considered as a MIP with 2 MeV/(g/cm^2)
$\rightarrow$ 2 MeV in 1 cm scintillator
$\rightarrow$ 2 keV in 1 cm of gas
To stop a 450 GeV muon beam, will need 900 m of concrete (density 2.5) !

How many meters of air to stop an α particle of 2 MeV ?

Particle with very low β (below the minimum ionization)
dE/dx around 700 MeV /(g/cm^2) and ρ =1g/l $\rightarrow$ 0.7 MeV/cm

Can stop α in 2-3 cm of air

Multiple scattering

❑ A charged particle traversing a medium is deflected by many small-angle scatters mainly due to Coulomb scattering from nuclei → multiple scattering. Affects precision of tracking performance
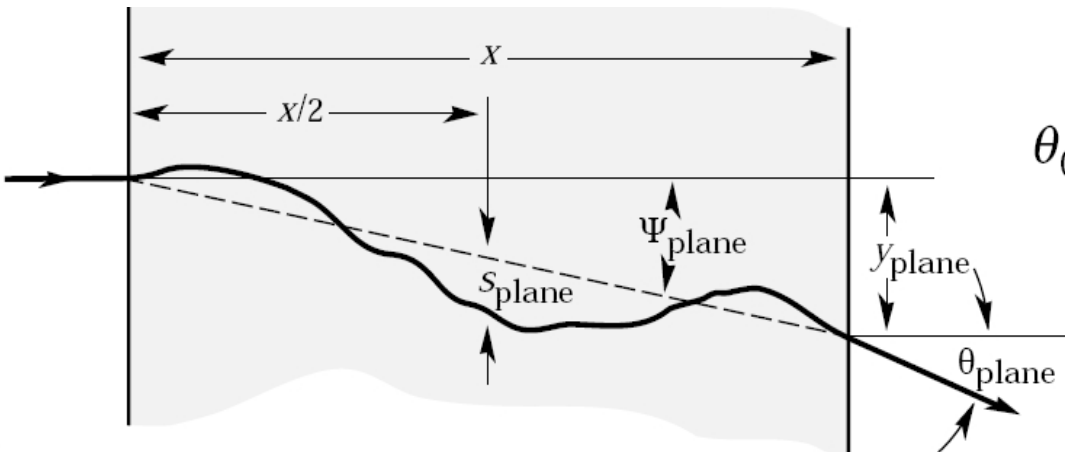
$$\theta_0 = \frac{13.6\,MeV}{\beta c p}\, z \sqrt{\frac{L}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{L}{X_0}\right) \right\}$$

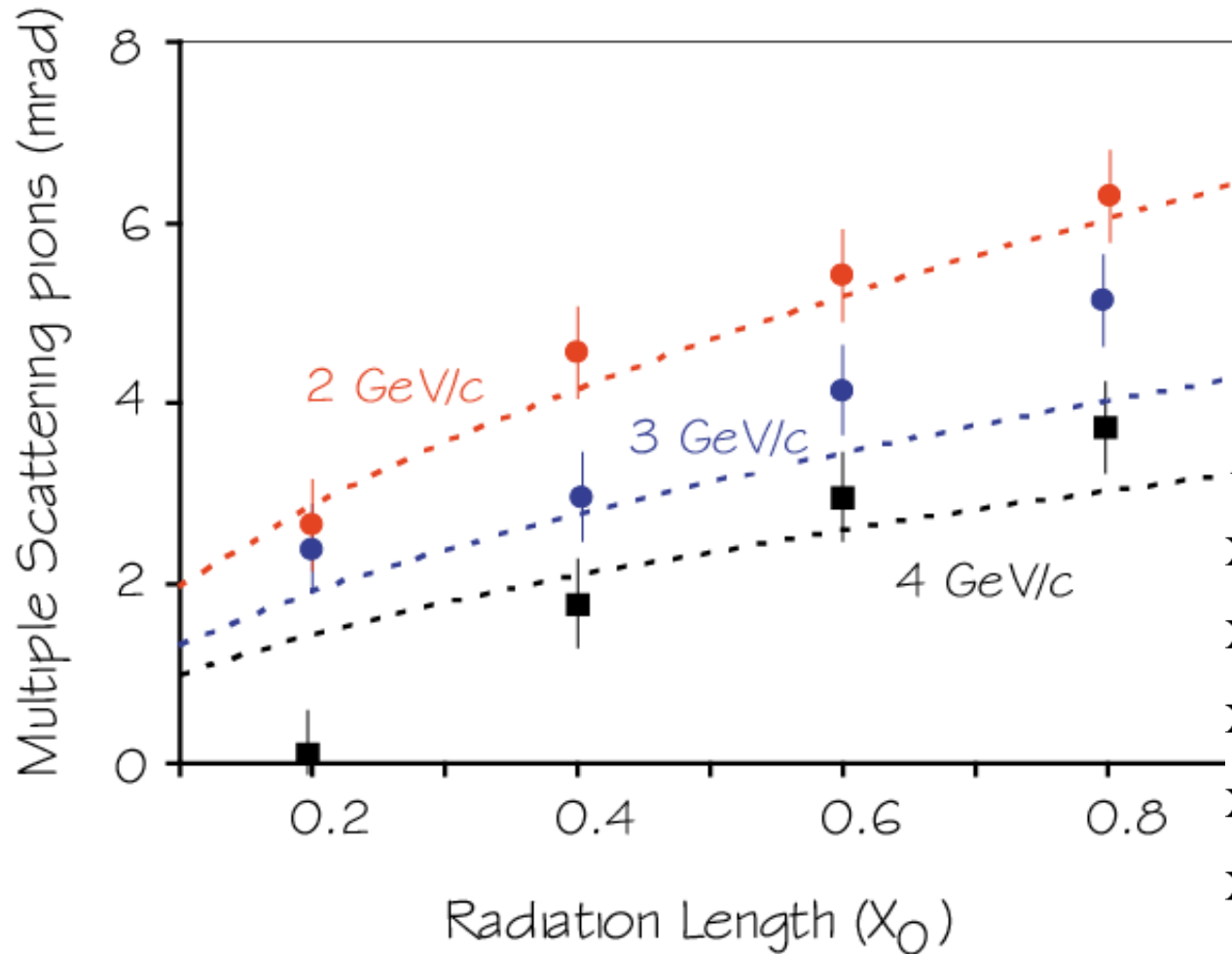Smaller for high energy,
for small material depth as
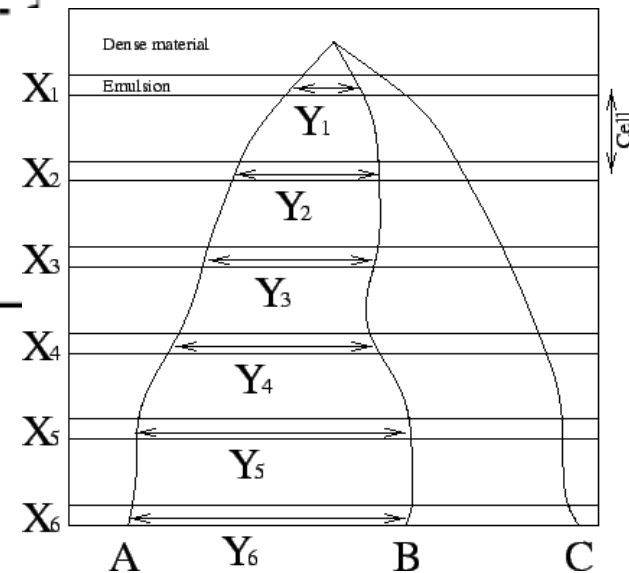measured in units of radiation
length

➜ Minimum of material
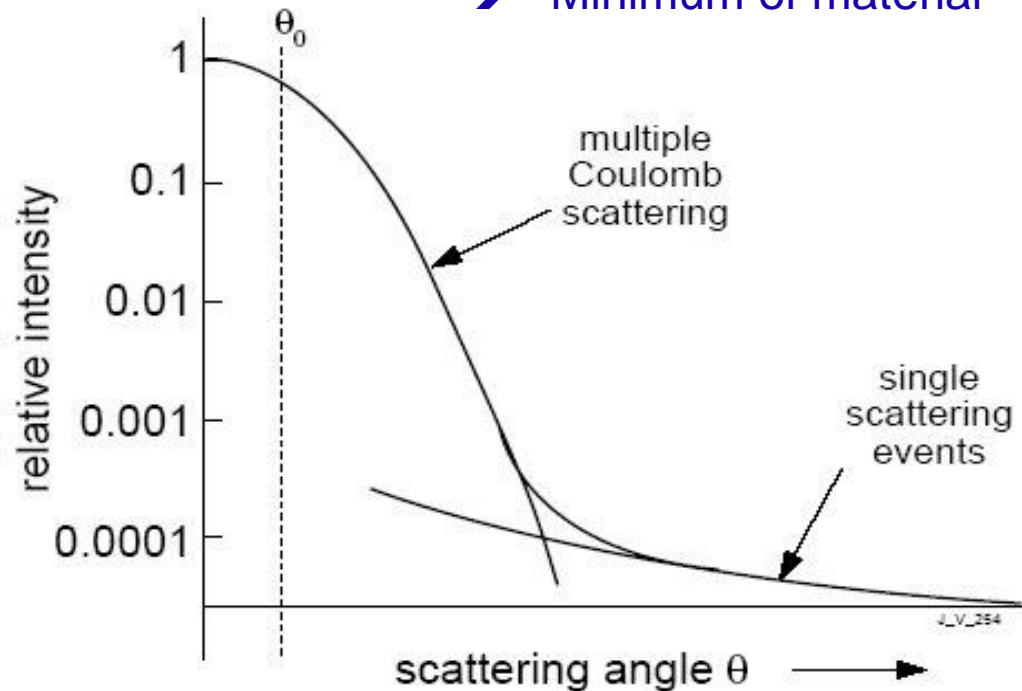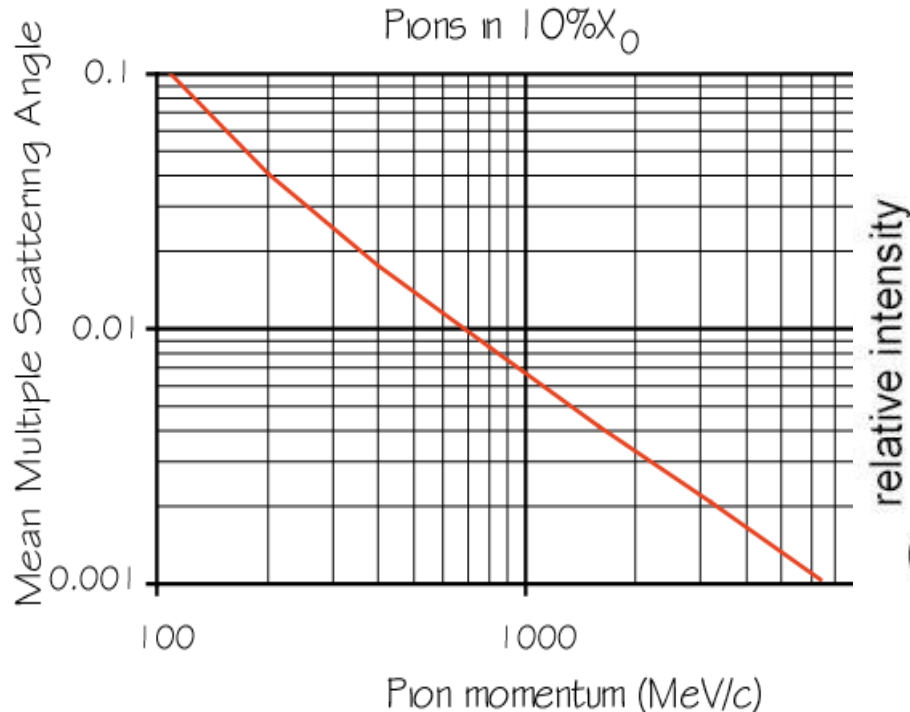
Effect of "0" if averaged for many particles, and seen as a fluctuation on a given one

and
(if you have no magnet) you can use it for measuring momentum

OPERA

… not the best means for measuring momentum though.

Electrons (and positrons) are different as they are light.

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

❑ Excitation/ionization

But collision between identical particles + electron is now deflected

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

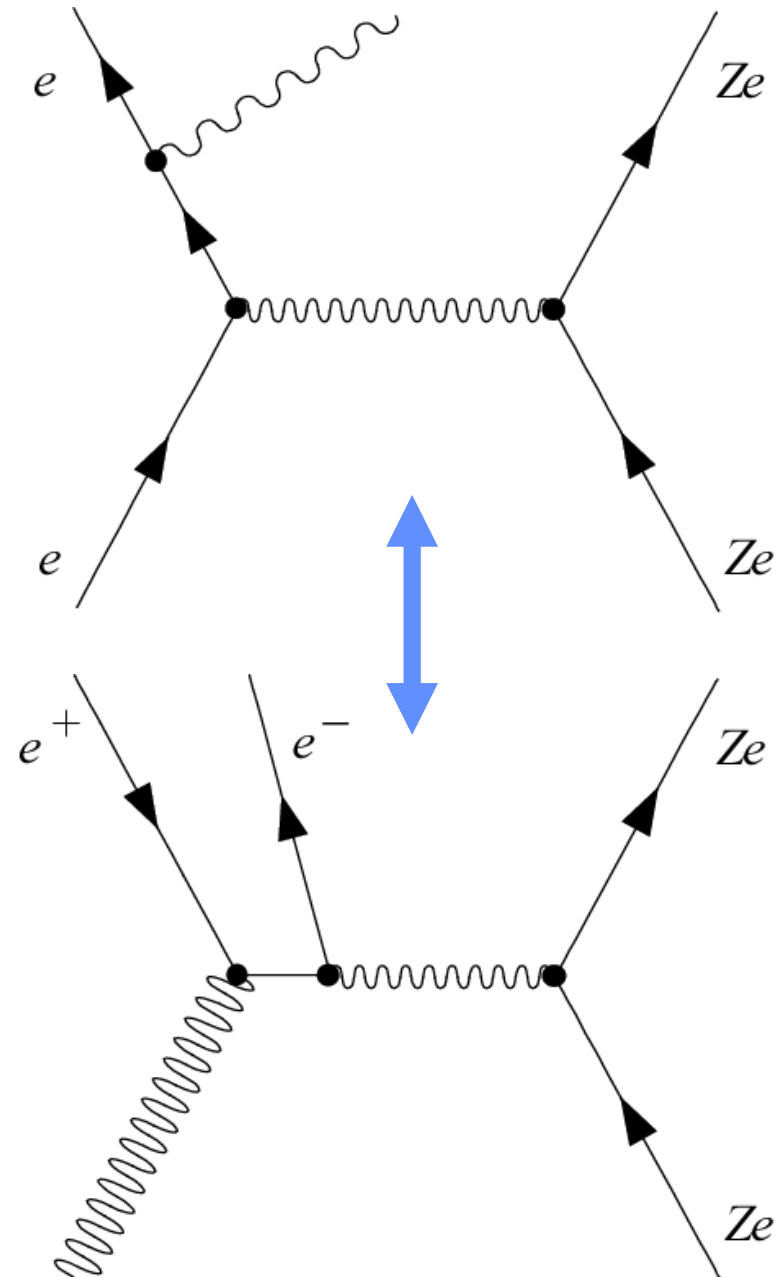*At high energies radiative processes dominate*

Bremsstrahlung

Bremsstrahlung is the emission of photons by a charged particle accelerated in the Coulomb field of a nucleus.
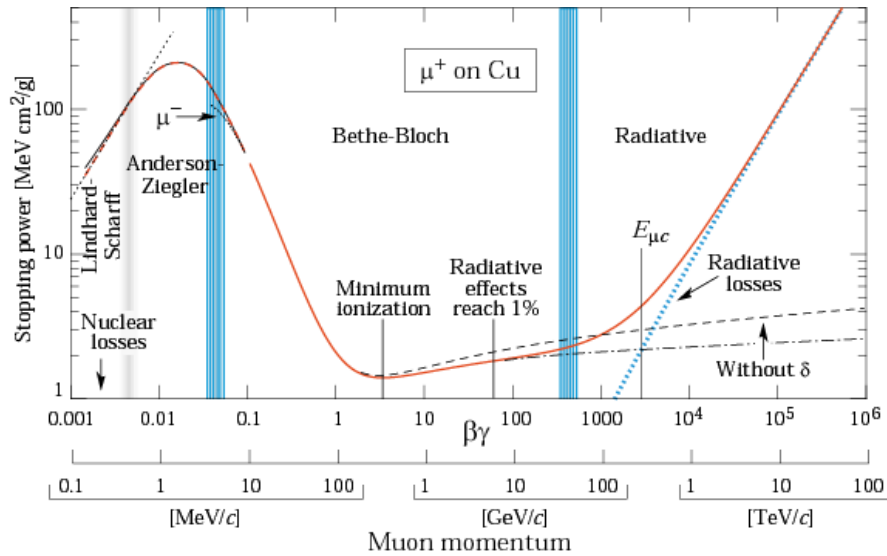
➔ *we now have an additional photon*

Pair production

Creation of an electron/positron pair in the field of an atom.

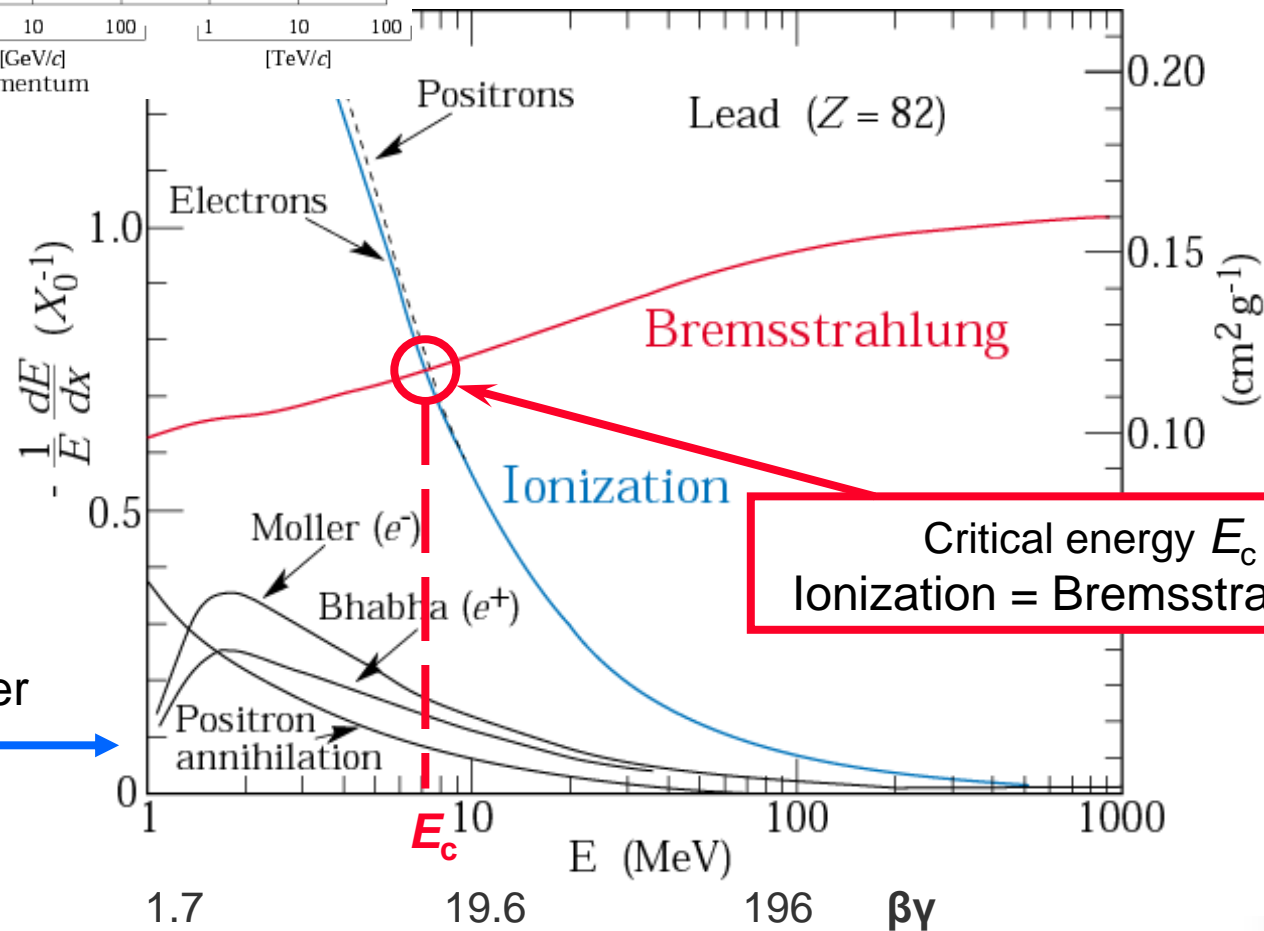➔ *we now have e+e- pair instead of initial photon*

Bethe-Bloch for heavy particles

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

Critical energy E_c
Ionization = Bremsstrahlung

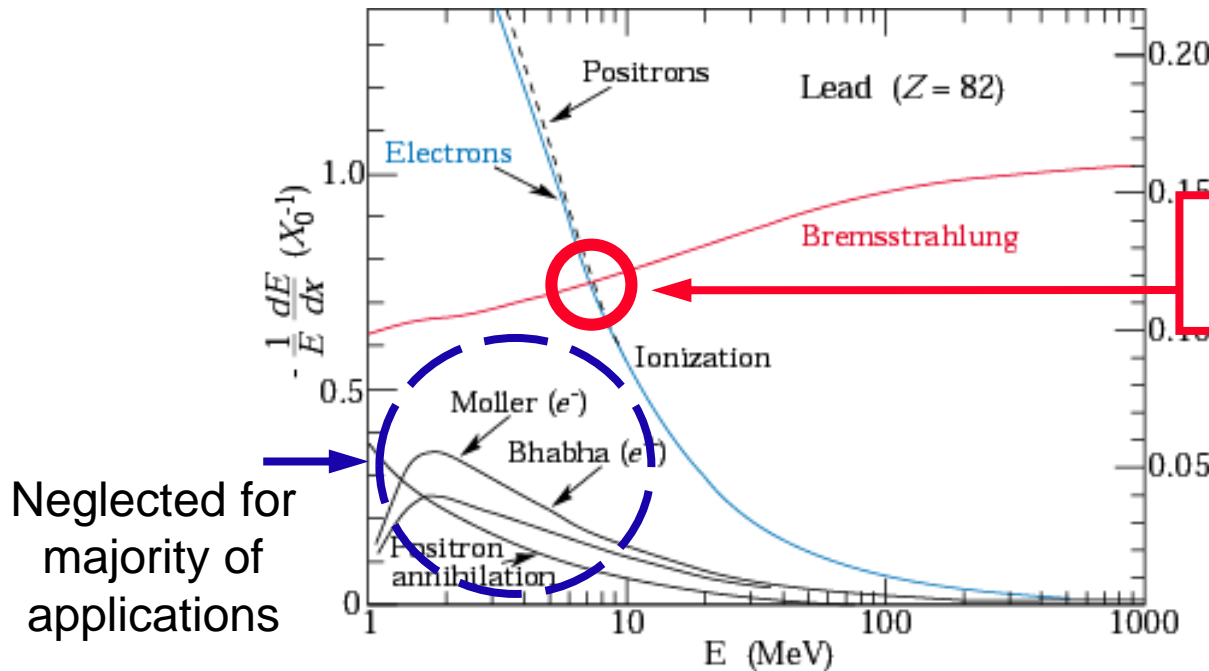Electron (positron)
interaction with matter

Define Radiation Length X_o
as the Radiative Mean Path :

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

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]

Approximation:

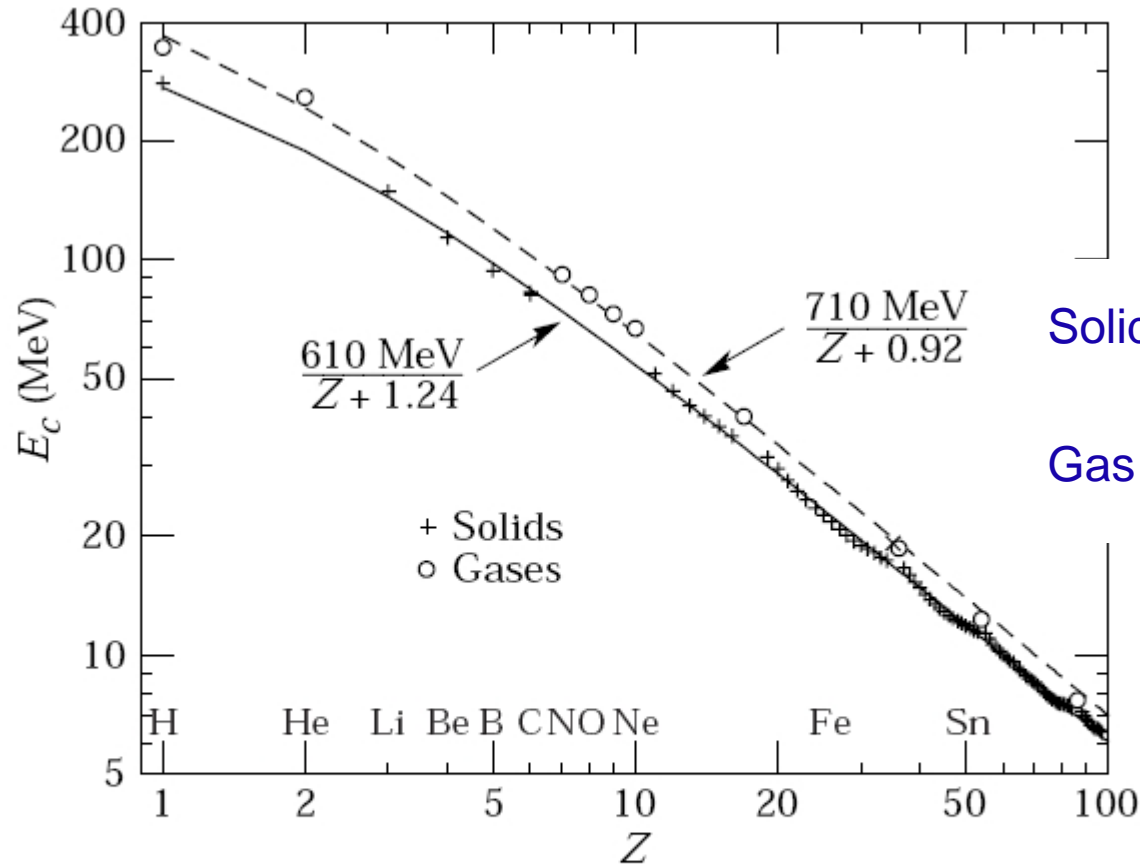$$X_0 = \frac{716.4 \, \text{g.cm}^{-2} A}{Z(Z+1)\ln(187/\sqrt{Z})}$$

Critical energy E_c
Ionization = Bremsstrahlung

Neglected for majority of applications

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

No simultaneous description of Ec for solids and gases (density effect)

➔ fits to the data

Solid : $E_c = \dfrac{610 \text{MeV}}{Z + 1.24}$

Gas : $\text{И} E_c = \dfrac{710 \text{MeV}}{Z + 0.92}$

Figure 27.13: Electron critical energy for the chemical elements, using Rossi's definition [4]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

Energy loss for photons $\rightarrow$ three major physics mechanisms :

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

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

Strong dependence with Z, dominant at low photon energy
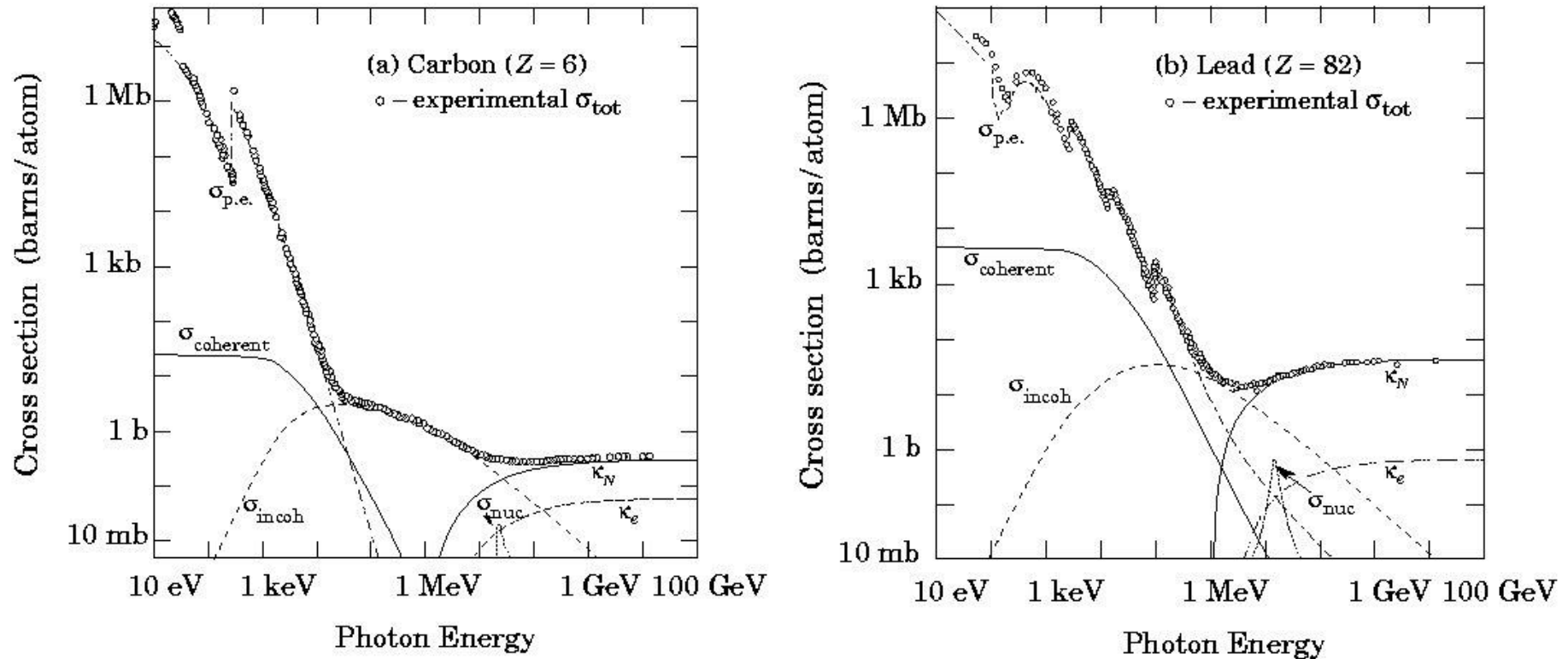
❑ Compton scattering
$$\sigma_C^e \propto \frac{\ln E_\gamma}{E\gamma} \text{ and atomic compton} = Z \, \sigma_C^e$$

❑ Pair creation (similar to Bremsstrahlung) : dominant for E >> $m_e c^2$

$$\sigma_{pair} \approx 4\alpha r_e^2 Z^2 (\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}}) = \frac{A}{N_A} \frac{7}{9} \frac{1}{X_0} \quad \text{Independent of energy !}$$

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 $\Lambda_{pair} = 9/7 \, X_0$

$\sigma_{\mathrm{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)

$\sigma_{\mathrm{Rayleigh}}$ = Rayleigh (coherent) scattering–atom neither ionized nor excited

$\sigma_{\mathrm{Compton}}$ = Incoherent scattering (Compton scattering off an electron)

κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{\mathrm{g.d.r.}}$ = Photonuclear interactions

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 $\{g/cm^2\}$	Nuclear[a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\vert_{min}$[b] $\left\{ \dfrac{MeV}{g/cm^2} \right\}$	Radiation length[c] X_0 $\{g/cm^2\}$	$\{cm\}$	Density $\{g/cm^3\}$ $(\{g/\ell\}$ 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		—

A high energy electron or photon incident on a thick absorber, initiates an EM cascade as pair production and Bremsstrahlung generate more electrons and photons with lower energy.
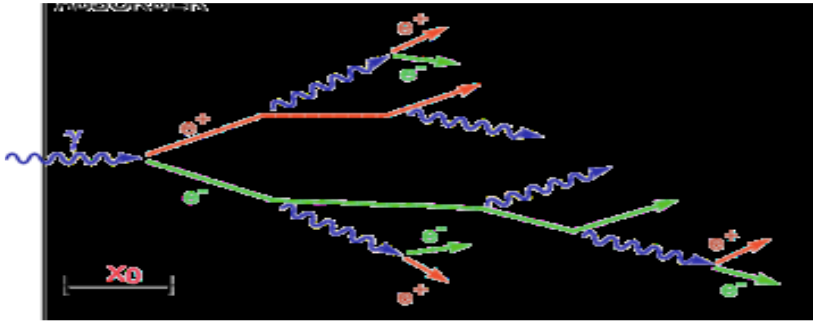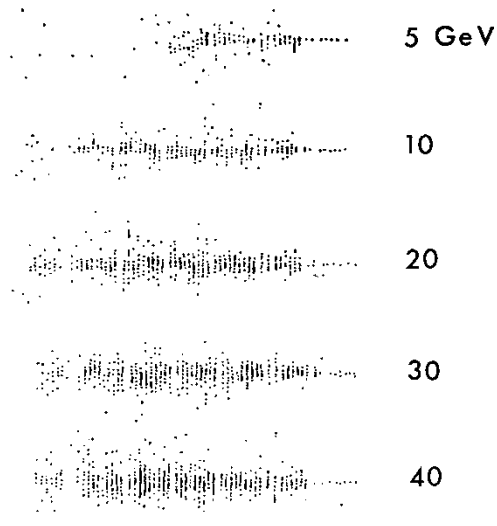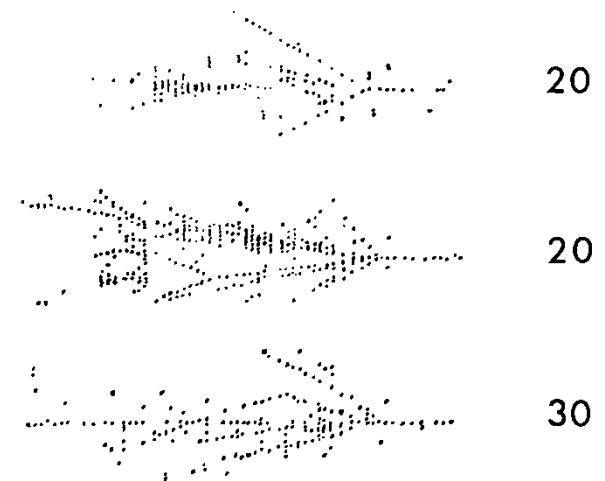

EM shower development
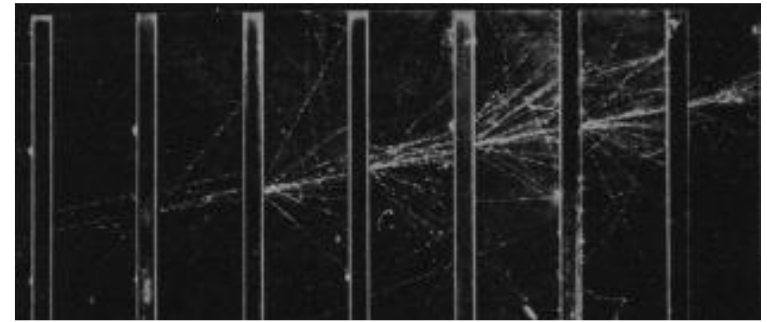
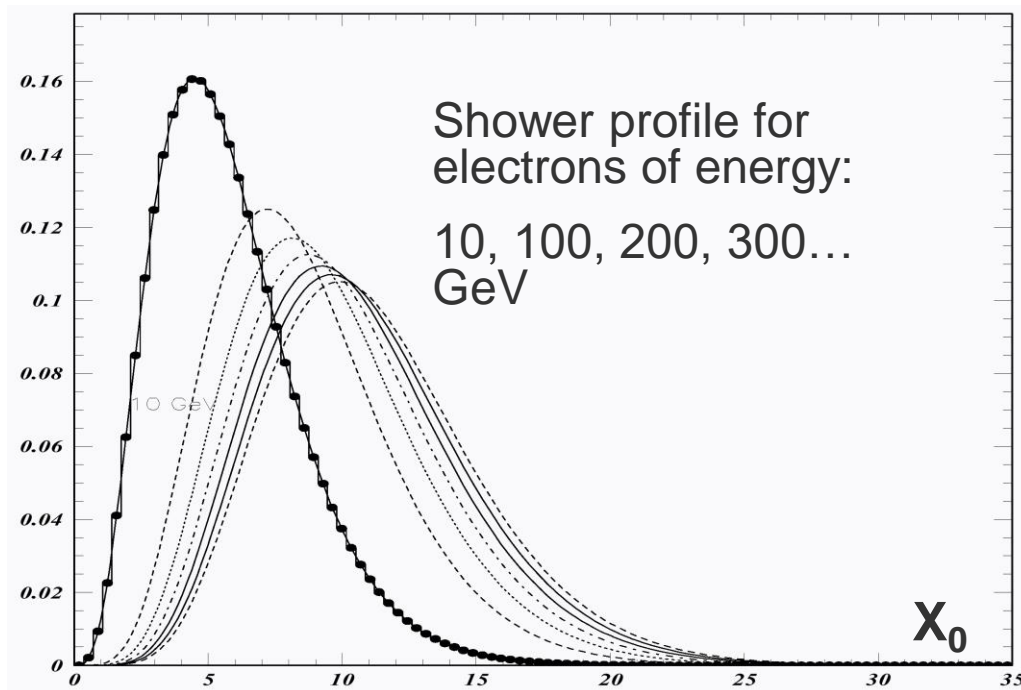**Lead absorbers in cloud chamber**

Electron showers

5 GeV

10

20

30

40

Hadron showers

20

20

30

F.E. Taylor et al., IEEE NS 27(1980)30

Longitudinal profile

Shower profile for electrons of energy:

10, 100, 200, 300… GeV

X_0

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 $1X_0$

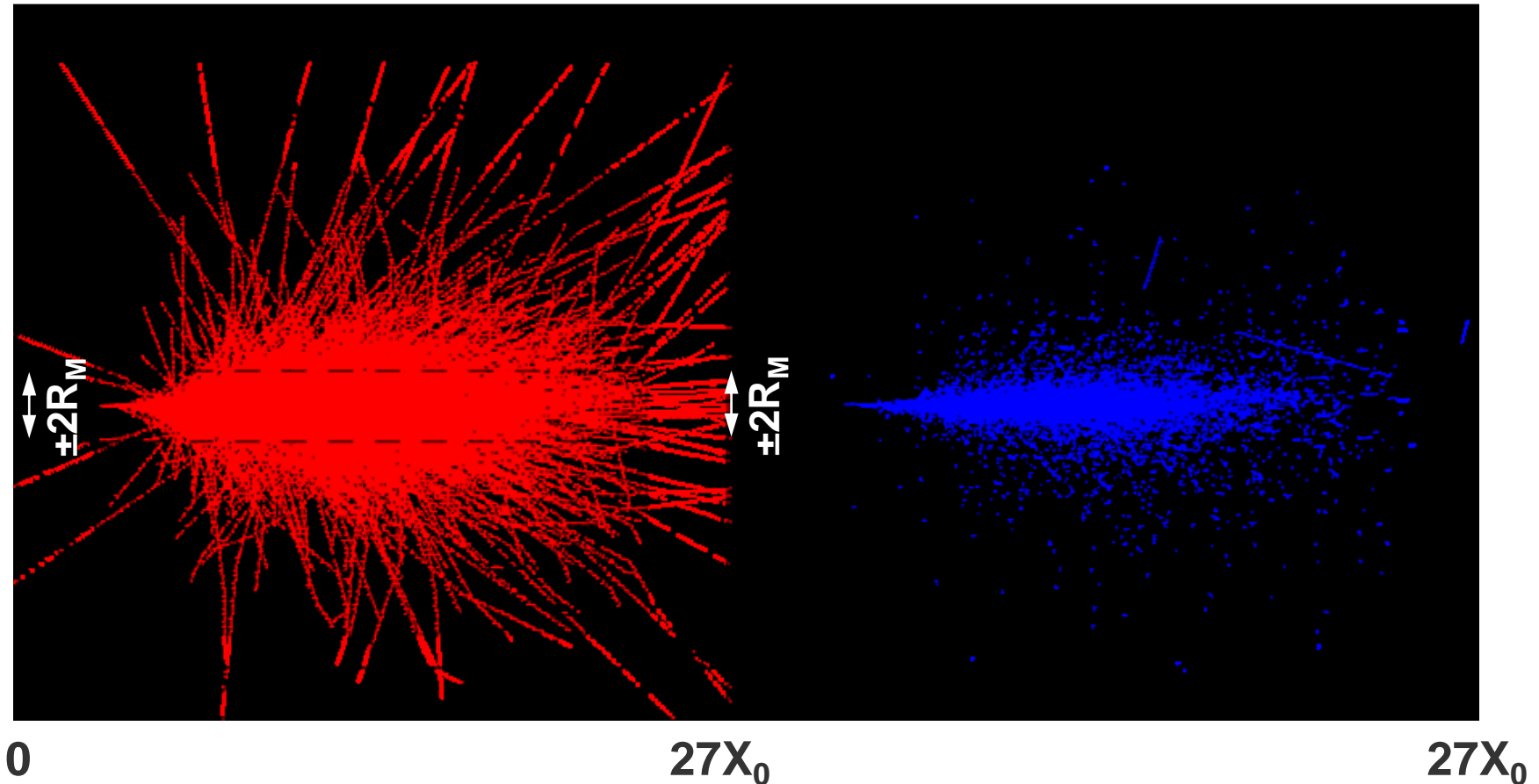$$R_M = \frac{21\text{MeV}}{E_C} X_0 \ (Z \gg 1)$$

Transverse shower containment:
90% E_0 within **$1R_M$, 95%** within **$2R_M$, 99%** within **$3.5R_M$**

From M. Diemoz, Torino 3-02-05

❑ EM shower development in liquid Krypton (Z=36, A=84)

Photons created **Charged particles created**

0 $27X_0$ $27X_0$
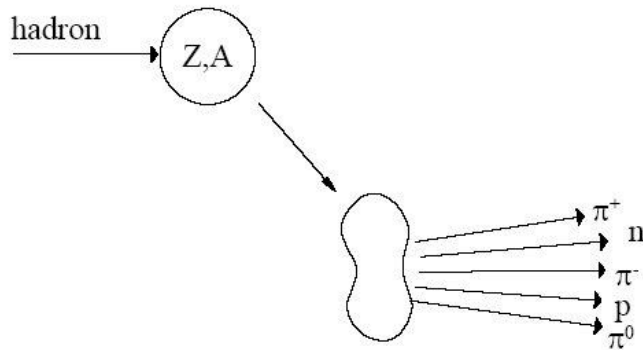
GEANT simulation: 100 GeV electron shower in the NA48 liquid Krypton calorimeter

From D. Cockerill

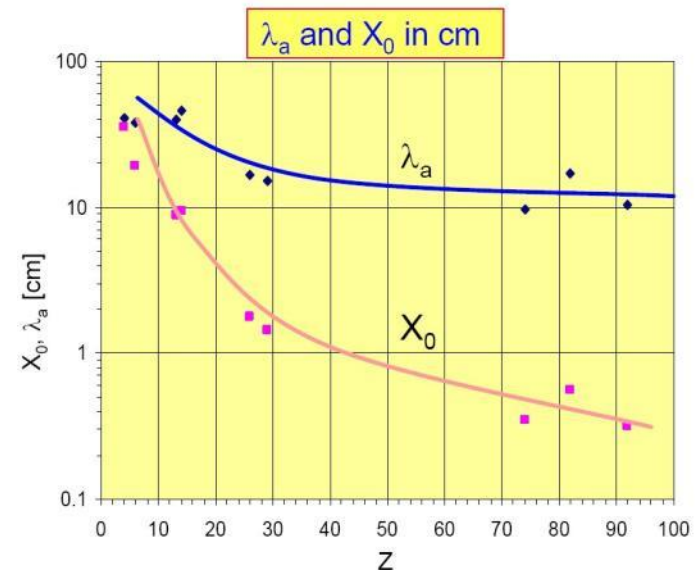Interaction of energetic hadrons (charged/neutral) through matter involves nuclear interaction :

excitation and nucleus break up => production of secondary particles + fragment

Number of particle produced ~ln (E) with average transverse p of 0.35 GeV/c

For E > 1 GeV, σ ~ $\sigma_0 A^{0.7}$, with σ_0= 35 mb and independent of particle type π,p,K,…
Convenient to introduce the hadronic interaction (absorption) length :

$$\lambda_{I(a)} = \frac{A}{N_A \sigma_{total(inel)}} \propto A^{1/3} , N = N_0 e^{-\frac{x}{\lambda_a}}$$

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 {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{min}$ [b] $\left\{ \frac{MeV}{g/cm^2} \right\}$	Radiation length [c] X_0 {g/cm^2} {cm}		Density {g/cm^3} ({g/ℓ} 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		—

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 → α + ^{3}H, n+^{3}He→p+^{3}H   E < 20 MeV

❑ n + p → 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 …

L. Serin

TP37 : neutron fluence ($n/cm^2/yr$)
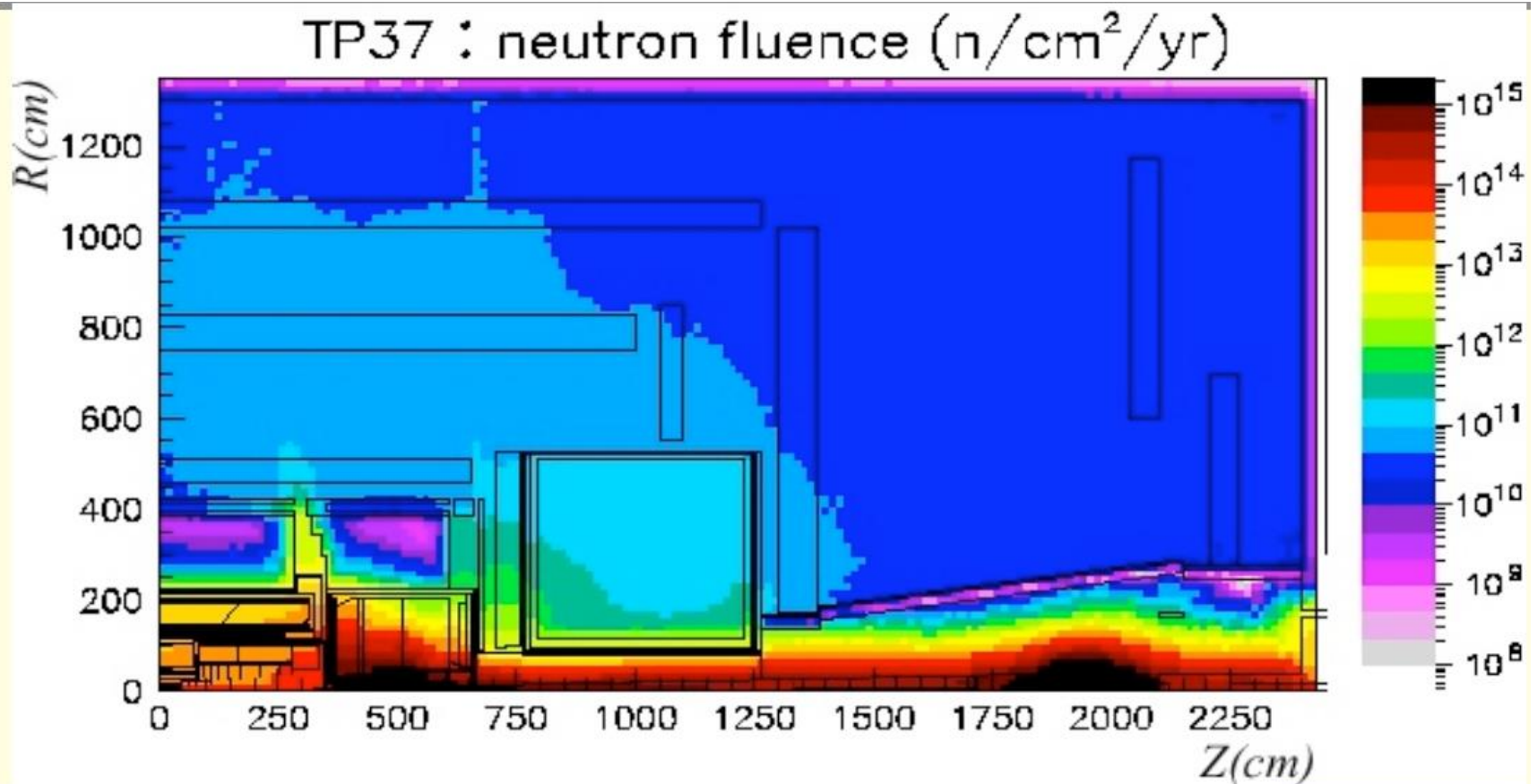
At r=11 cm, photons flux of 30 MRad !

100 Rad ~ $6.24 10^{12}$ MeV/kg deposited energy (1J/kg)

Strong constraint on detector technology and electronics : ageing in gaseous detectors
light loss (transparency) in scintillators/cerenkov, atom displacement in solid detectors

❑ 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 e+e- collider experiment, indirect detection :

  ❑ "Fully" hermetic detector (!)

  ❑ Sum all visible energy/momentum

  ❑ Use beam energy constraint ➔ neutrino(s) are taking the missing energy/momentum

Bethe-Bloch for heavy charged particles

2 MeV / (g/cm2) for a MIP
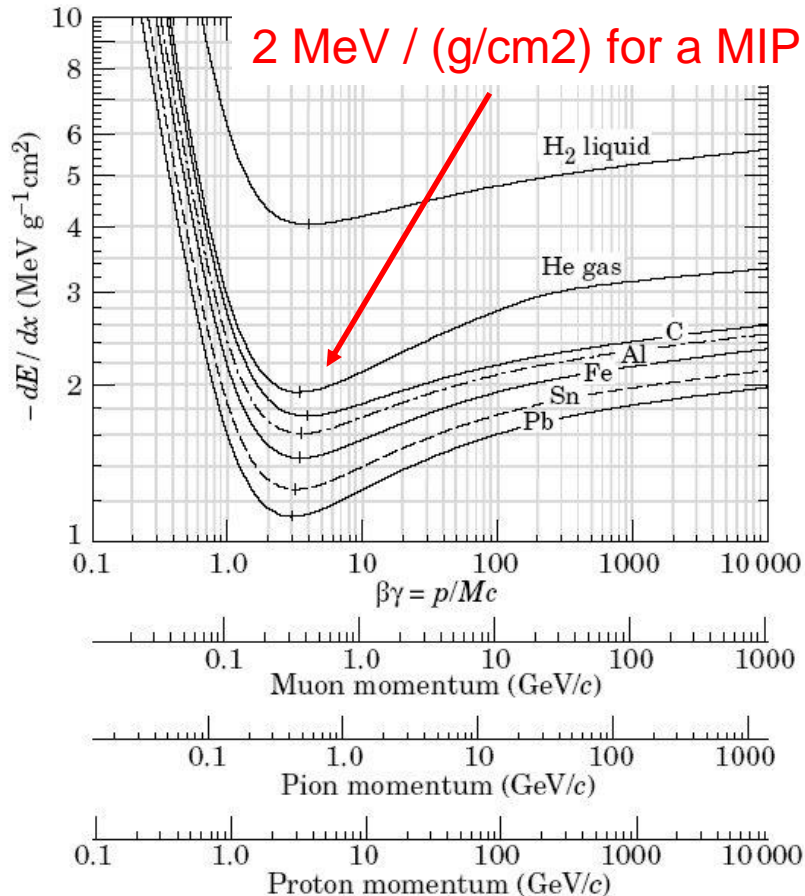
Radiation length X_0

e^+ / e^-

γ
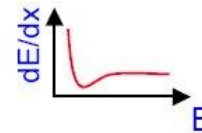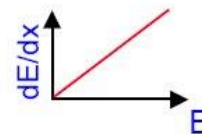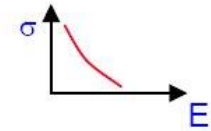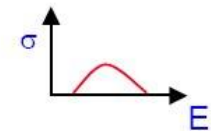
- Ionisation
- Photoelectric effect
- Bremsstrahlung
- Compton effect
- Pair production
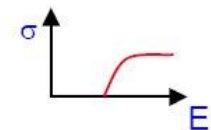
Interaction of hadrons : many different particles produced,

interaction length λ_I

Now we are (almost) ready to built our first detector …

… but let us first look through common methods and tools

Gaseous detectors

Measure: hit and/or drift time
→ Position resolution: ~ 50 µm
    → Tracks reconstruction
+ Magnetic field
    → Momentum

[Measure also: energy loss dE/dx
→ Particle ID]

http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html
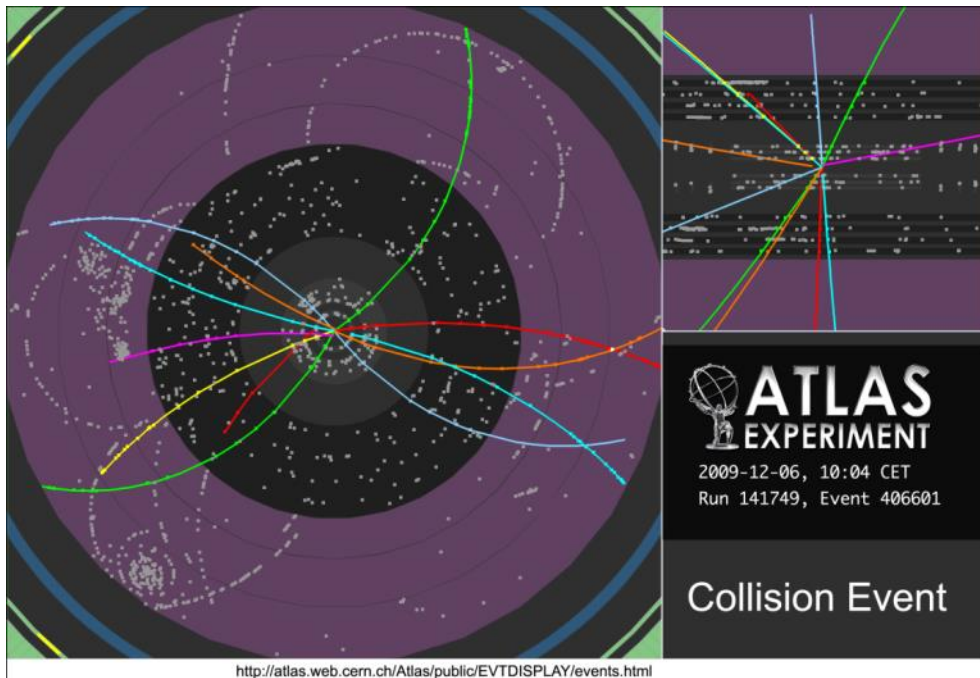
candidate as reconstructed in the Inner Tracker

K_S → π+π-
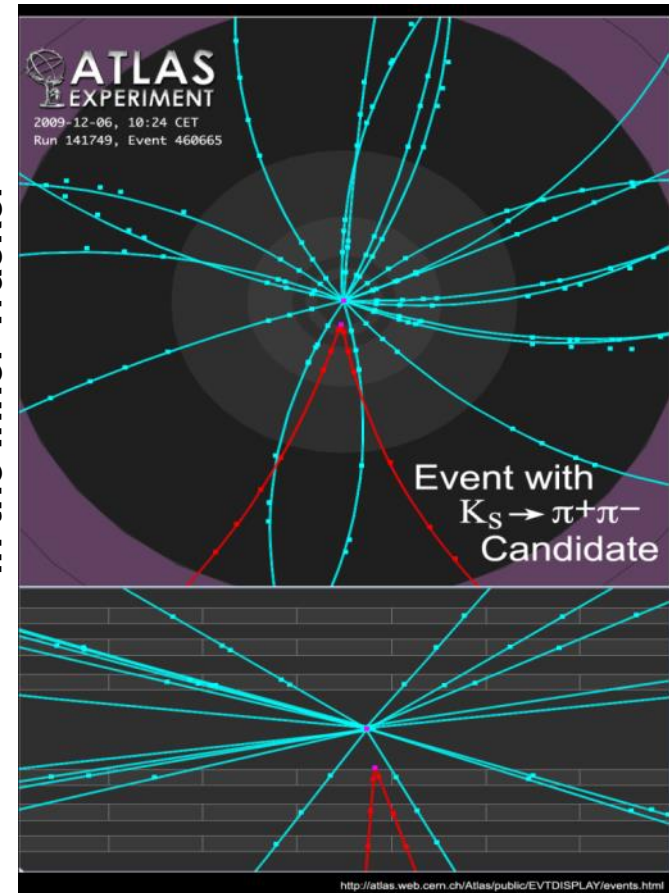
Silicon detectors

Measure: hits and/or amplitude
→ Position resolution: ~ 5 µm
→ Tracks & **Vertices** reconstruction

Cherenkov detectors

Measure: Cherenkov radiation angle (threshold)
➔ Particle ID

Example: LHCb Ring Imaging CHerenkov detector RICH

Radiator
+ Cherenkov light
measurement
+ …
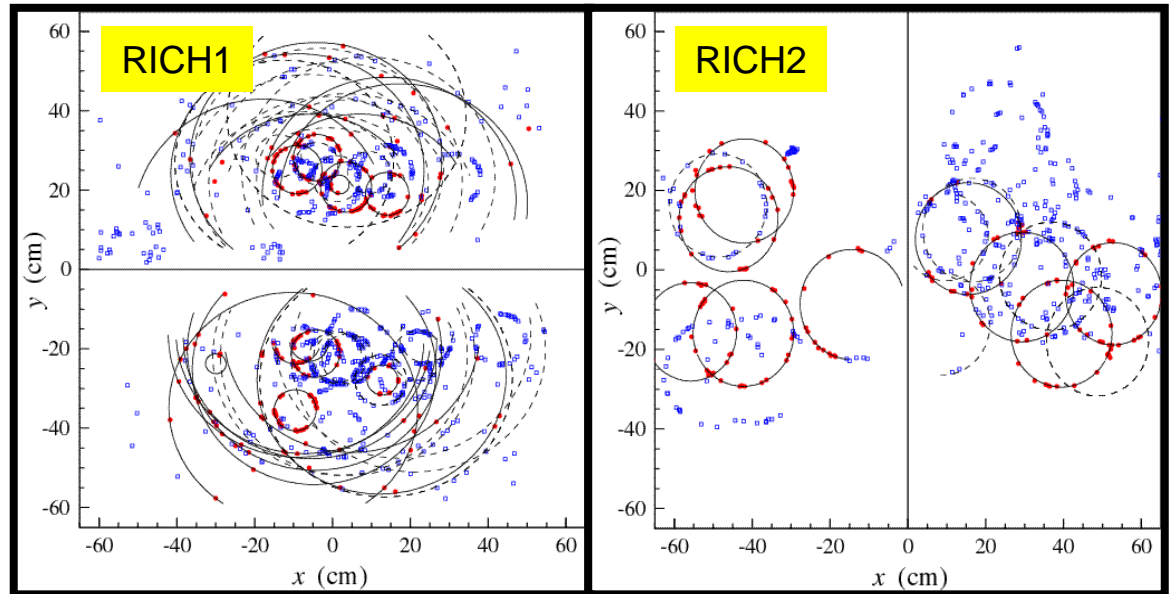
+ Transition radiation detectors
+ dE/dx from tracking detectors
+ Time-Of-Flight
+ …

Calorimeters: electromagnetic and hadronic

Measure: shower energy and/or shower shape
➔ Energy resolution
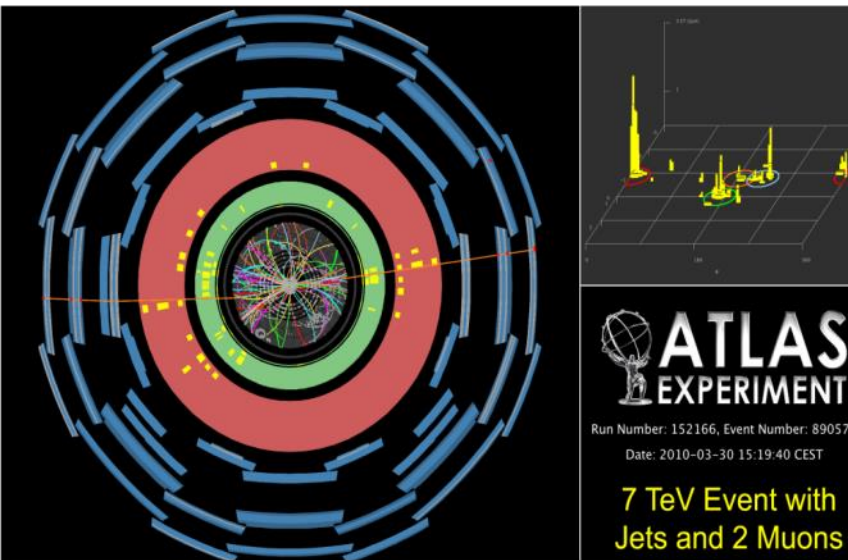➔ Position resolution:
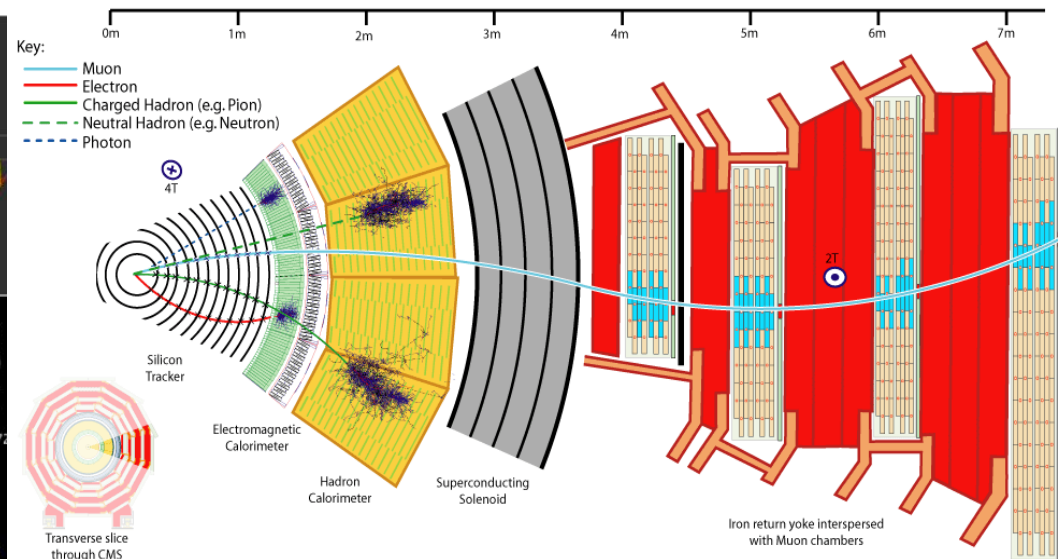   ~few mm
➔ Particle ID

Muon detectors   Measure: Muon track after absorber
   ➔ Particle ID

Muons in ATLAS

Muon in CMS

❑ **Efficiency** ~ amount of signal and Intrinsic **detector resolution**

- ❑ *Spatial resolution* → degrade mass resolution via momentum measurement; contribute to combinatorial background via picking up random tracks and via PID.
- ❑ *Energy resolution* → degrade mass resolution via energy measurement; contribute to combinatorial background via PID.
- ❑ *Time resolution* → degrade mass resolution via contribution to spatial resolution in tracking devices; contribute to combinatorial background via pile-up and via PID.

Is the excess due to the decay of a particle into two photons ?
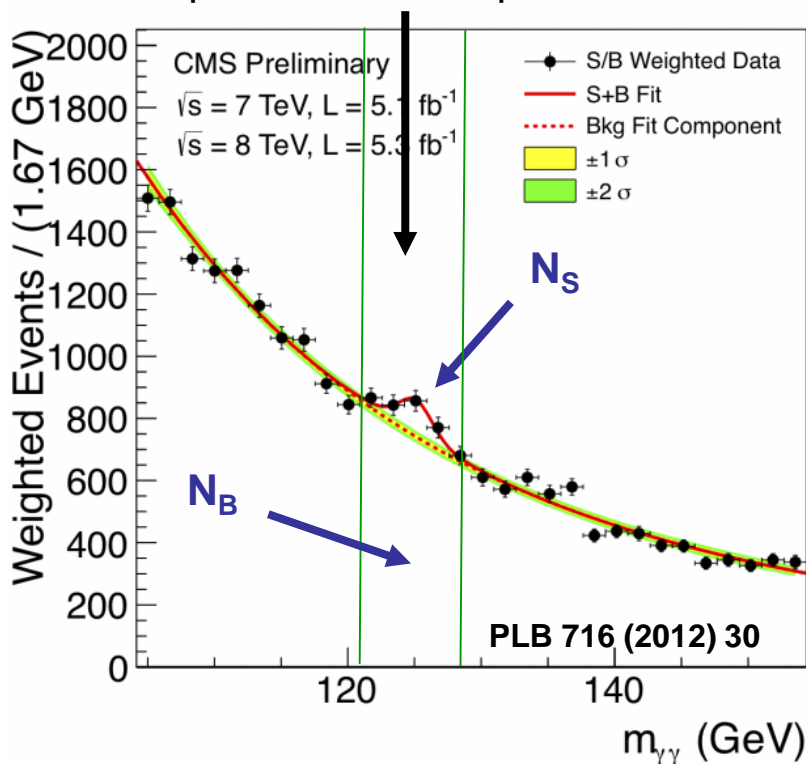
Statistical significance : $S = N_S / \sqrt{N_B}$

N_S (N_B) : Number of signal (background) events, estimated in the peak region
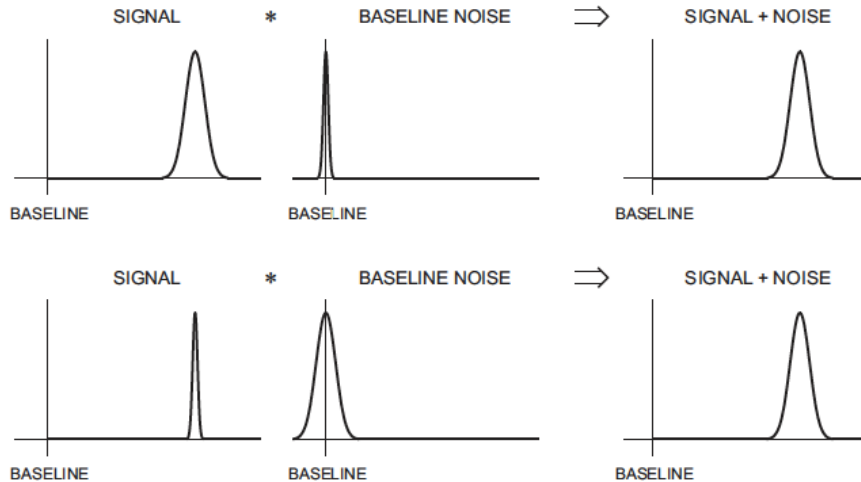
$$S \sim \varepsilon \sqrt{L / \sigma}$$

→ Enlarge data sample
→ Increase detector efficiency
→ Reduce detector resolution

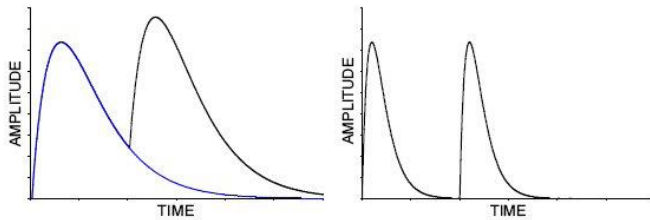Convention : S > 5 → Discovery

Criteria: efficiency and resolution

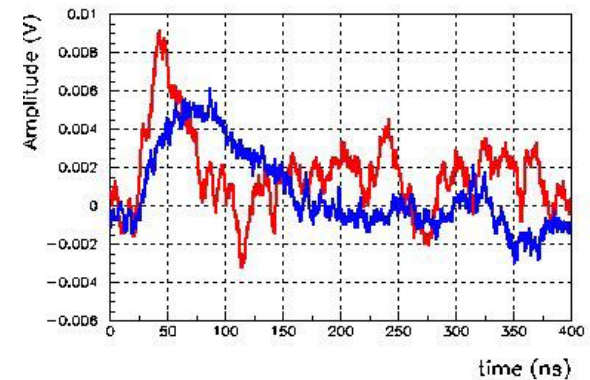❑ **Signal treatment** added to intrinsic detector resolution → **Read-out electronics** !

❑ Every signal comes with its noise

❑ Reduce pile-up

❑ Realistic signal + noise shape

After E. Garutti et al.

❑ **Signal treatment** added to intrinsic detector resolution → **Read-out electronics** !

    ❑ Example: ATLAS LAr calorimeter

    ❑ Ionization signal 500 ns ~ 20 LHC BXs

    ❑ Fast shaper reduces signal to 5 LHC BXs → less pile-up but higher electronics noise

    ❑ Choice of optimal timing varies with luminosity
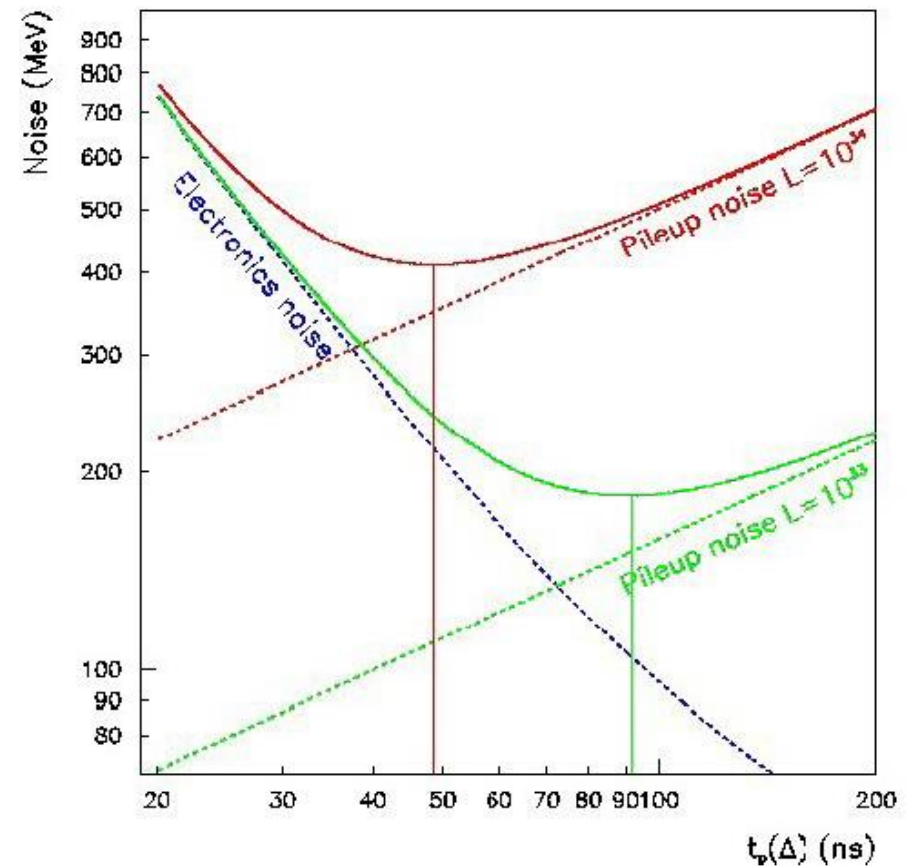
After E. Garutti et al.

- Minimum at $\beta\gamma \sim 3 \ldots 4$
- Similar for all elements
  ~ 2 MeV/(g/cm^2)

  ... why H2 is different ?
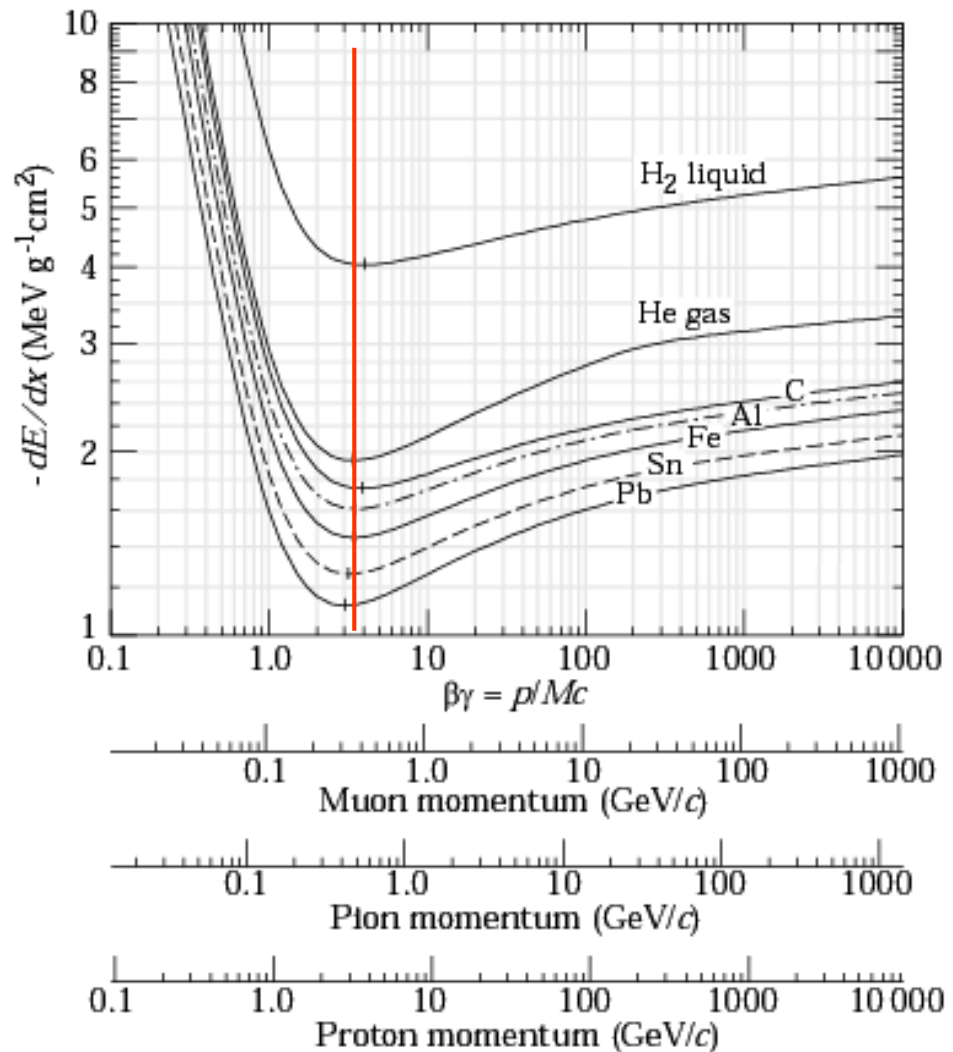
Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.

Silicon detectors   ➔   Position resolution: ~ 5 μm

Gaseous detectors   ➔   Position resolution: ~ 50 μm

Calorimeters   ➔   Position resolution: few mm

Why calorimeters are important for position measurements ?

Q3

Two electromagnetic showers are initiated by an electron and by a photon.

Which shower will penetrate deeper in the calorimeter ?