LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE

Instrumentation for high energy physics

Sergey Barsuk, LAL Orsay, sergey.barsuk@lal.in2p3.fr

- Passage of particles through matter
- Photon detectors
- Scintillators
- Cherenkov light detectors, time-of-flight detectors
- Calorimeters
- Tracking detectors: silicon and gaseous detectors, introduction

- Very selective and personal, no way to cover all technologies/detectors
- Many simplifications, avoid formalism where possible
- No proper references to the origin for many plots

TESHEP, Poltava - Ukraine, 13-20/07/2018

Some references

- Particle detectors, C. Grupen, Cambridge University
- Radiation detection and measurement, G. Knoll, John Wileys & sons
- Techniques for nuclear and particles physics experiments, W. Leo, Springer
- Experimental techniques in high energy physics, T. Ferbel, World Scientific

- Particle Data Book

- Excellent presentation of C. Joram at CERN summer student in 2002

- Dan Green, The Physics of Particle Detectors
- Fabio Sauli, Principles of Operation of Multiwire Proportional and Drift Chambers
- Richard Wigmans, Calorimetry
- Presentations/proceedings from many detector conferences

Some units and conventions

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

$$E^2 = \vec{p}^{\,2}c^2 + m_0^2 c^4$$

energy ***E*** :	measured in **eV**	
momentum ***p*** :	measured in eV/c	or **eV**
mass ***m*₀** :	measured in eV/c²	or **eV**

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

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

http://www.nature.com/news/2004/040105/images/bee_180.jpg

1 eV is a small energy.

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

$\boldsymbol{m}_{\mathbf{bee}} = 1\mathrm{g} = 5.8\cdot 10^{32}\ \mathrm{eV}$

$\boldsymbol{v}_{\mathbf{bee}} = 1\ \mathrm{m/s} \Rightarrow E_{\mathrm{bee}} = 10^{-3}\ \mathrm{J} = 6.25\cdot 10^{15}\ \mathrm{eV}$

$\boldsymbol{E}_{\mathbf{LHC}} = 14\cdot 10^{12}\ \mathrm{eV}$

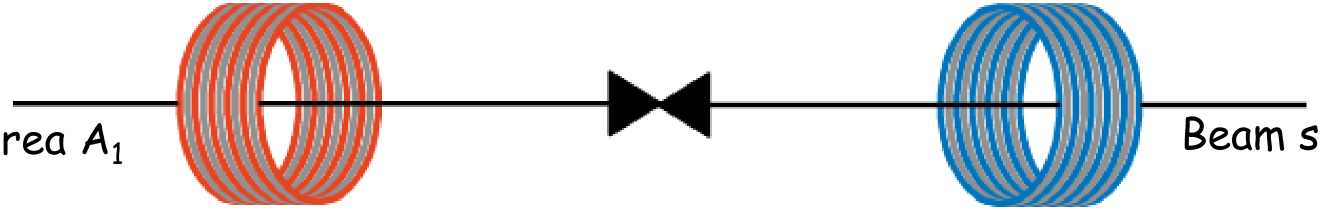
However,
LHC has a total stored beam energy
10^{14} protons x $14\cdot 10^{12}$ eV ~ 10^{8} J

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

from C. Joram, SSL 2003

Some units and conventions

Cross section σ or the differential cross section $d\sigma/d\Omega$ is an expression of the probability of interactions.



Beam spot area A_1

Beam spot area A_2

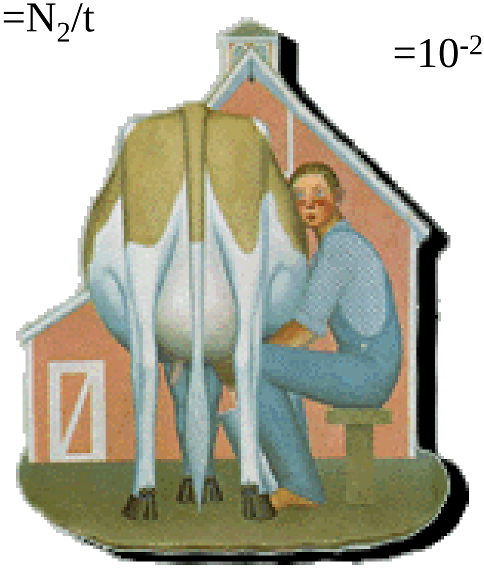
$F_1=N_1/t$

$F_2=N_2/t$

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

$$R_{\text{int}} \propto \frac{N_1 N_2}{A \cdot t} = \sigma \mathcal{L}$$

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



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

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

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

from C. Joram, SSL 2003

- ☐ At 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}

Ingredients for a typical HEP experiment :

- Find a nice region and build an accelerator there
- Design and build the detectors around BX points
- Add :
  - FE electronics
  - Trigger and DAQ
  - Control systems
  - Physicists to operate the detector and analyse data
- Requirement to all the ingredients correlated (more often anti-correlated ☹)

from J.Effel, Création du Monde

To reach unexplored area within HEP :

⇨ Increase Energy

⇨ Increase Luminosity

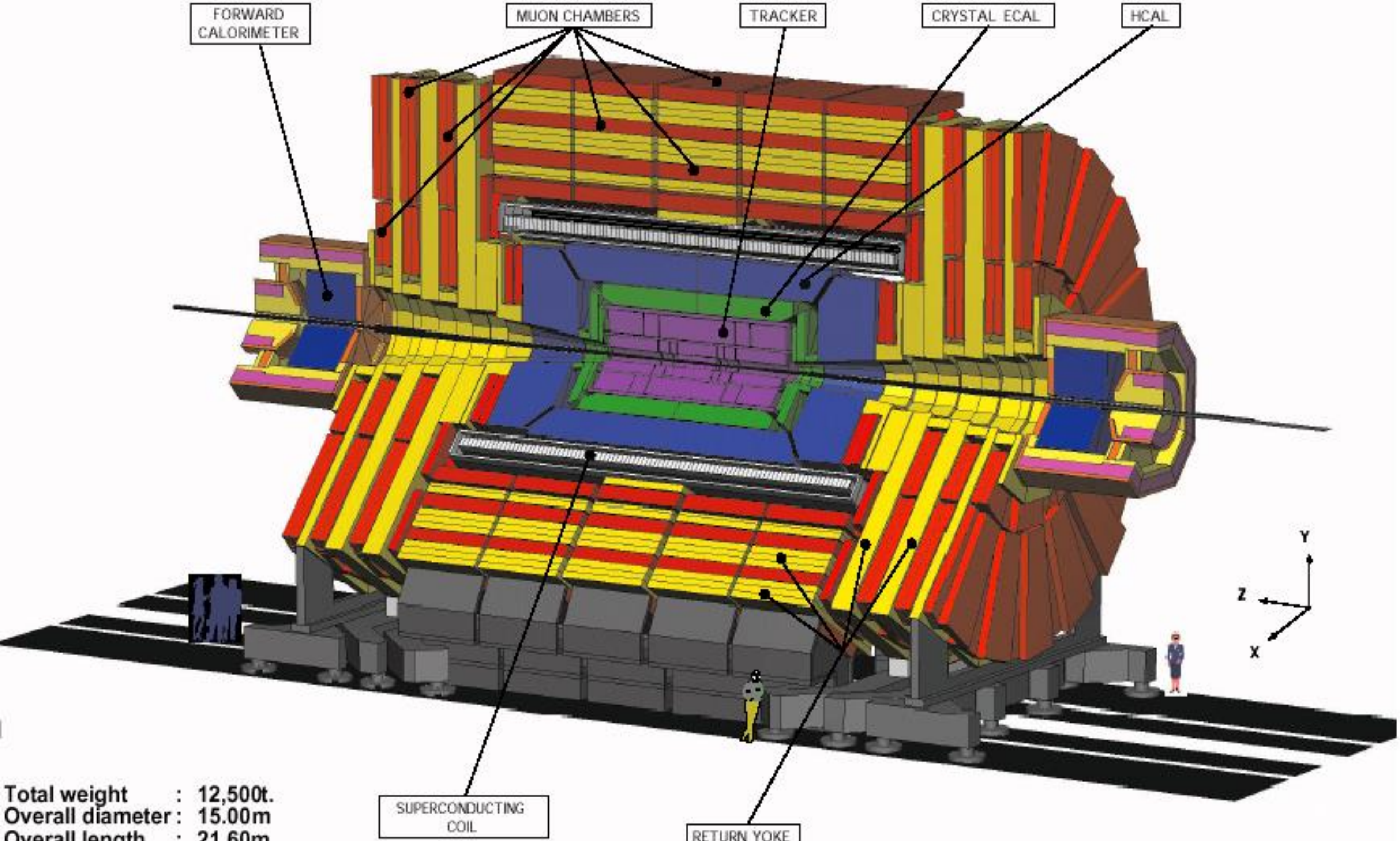
} Accelerators

⇨ Increase Precision

{ Theory & Analysis

Detectors

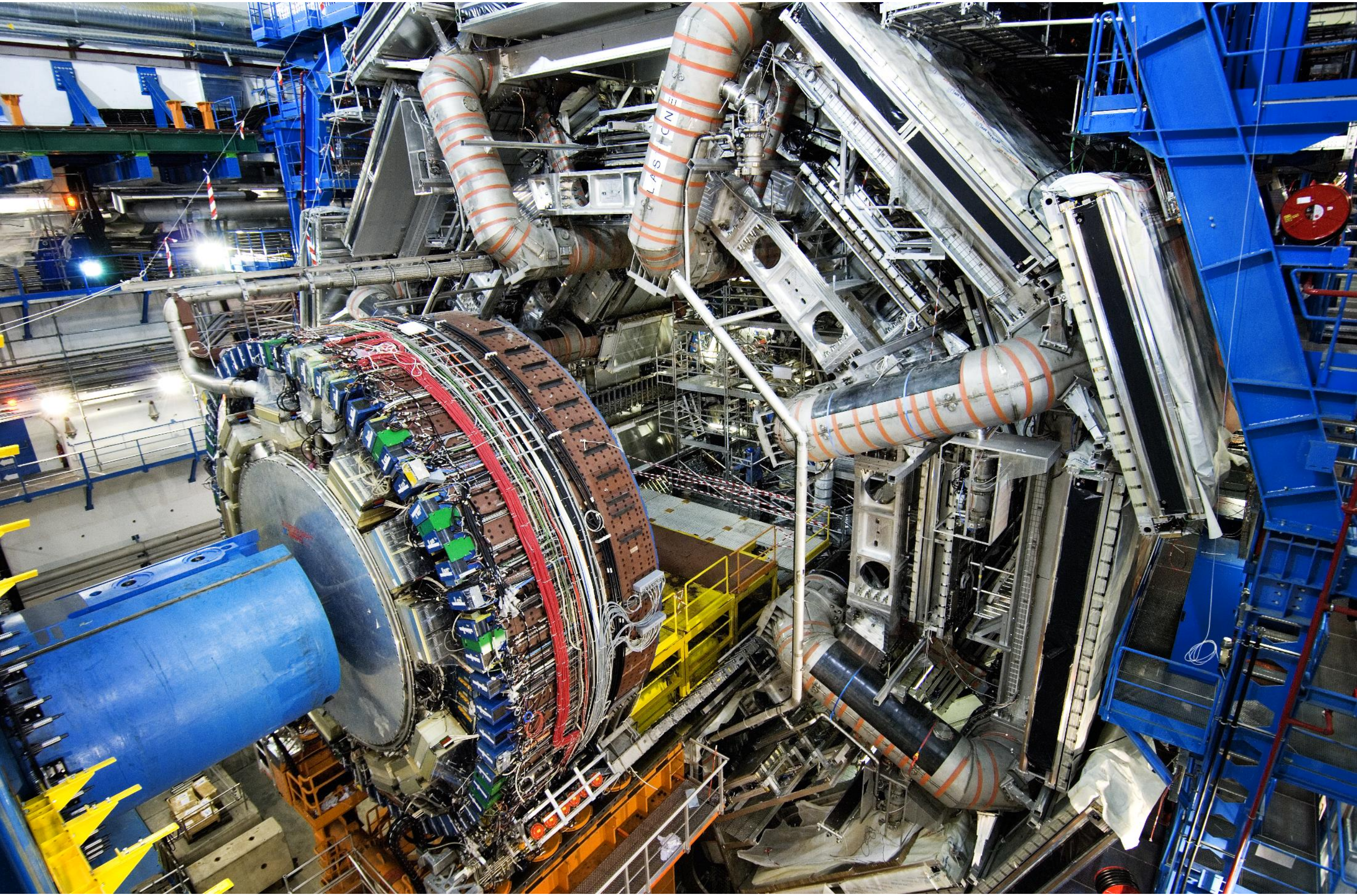
CMS
A Compact Solenoidal Detector for LHC



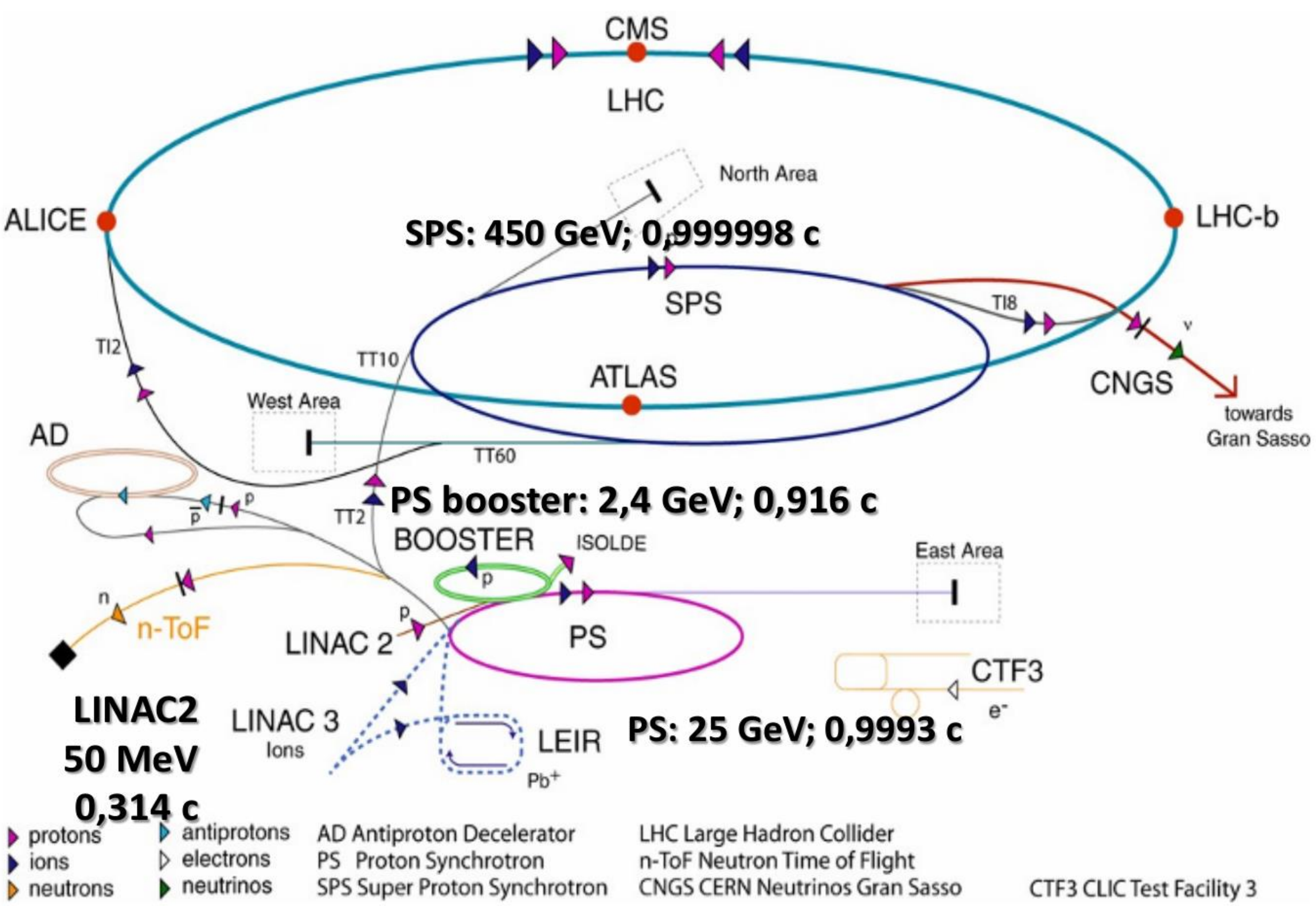
Total weight	:	12,500t.
Overall diameter	:	15.00m
Overall length	:	21.60m
Magnetic field	:	4 Tesla

CMS-PARA-001-11/07/97 JLB.PP

ATLAS detector



The CERN accelerator complex



SPS: 450 GeV; 0,999998 c

PS booster: 2,4 GeV; 0,916 c

PS: 25 GeV; 0,9993 c

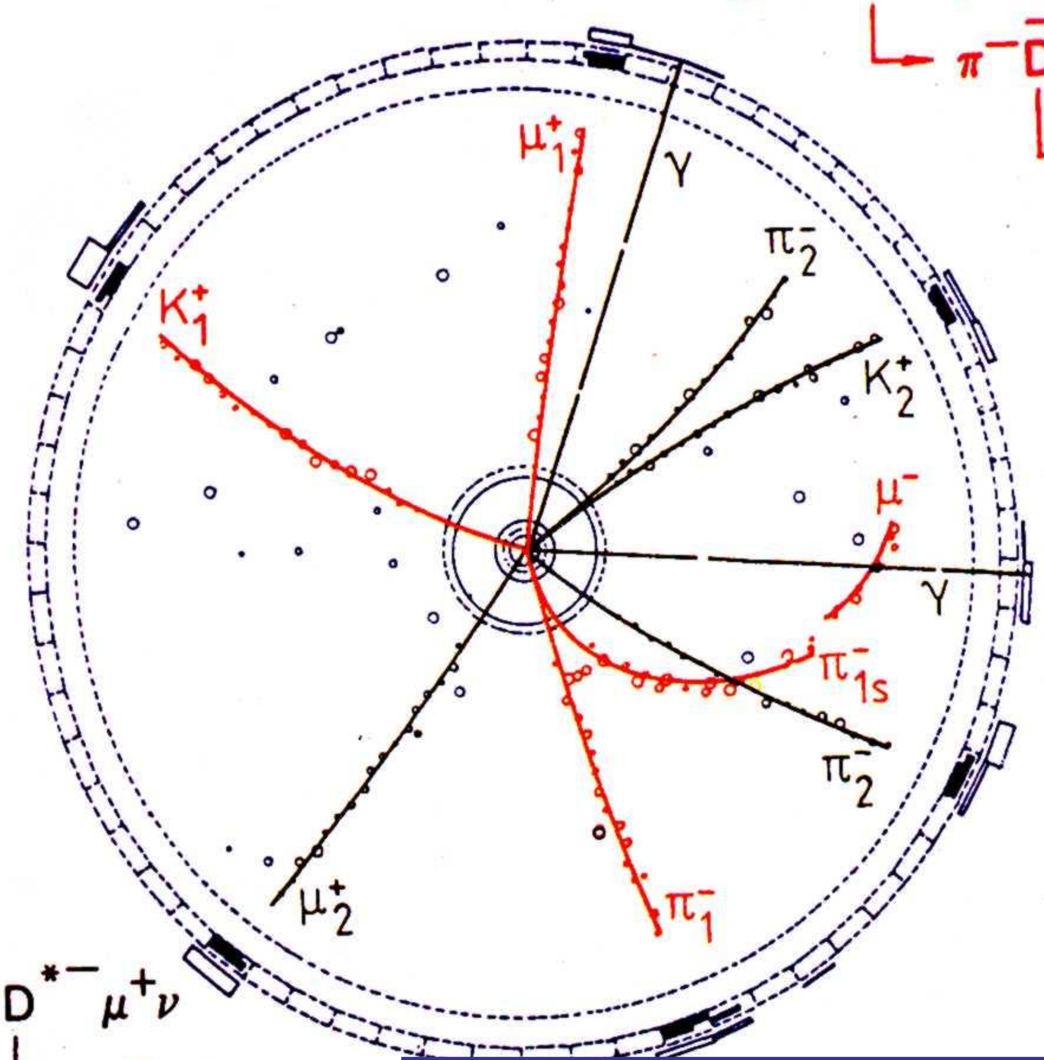
LINAC2
50 MeV
0,314 c

ARGUS

$B^0 \to D^{*-}\mu^+\nu$

└→ $\pi^-\bar{D}^0$

└→ $K^+\pi^-$



$B^0 \to D^{*-}\mu^+\nu$

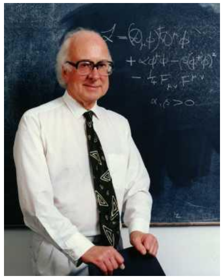
└→ $\pi^0 D^-$

└→ $K^+\pi^-\pi^-$

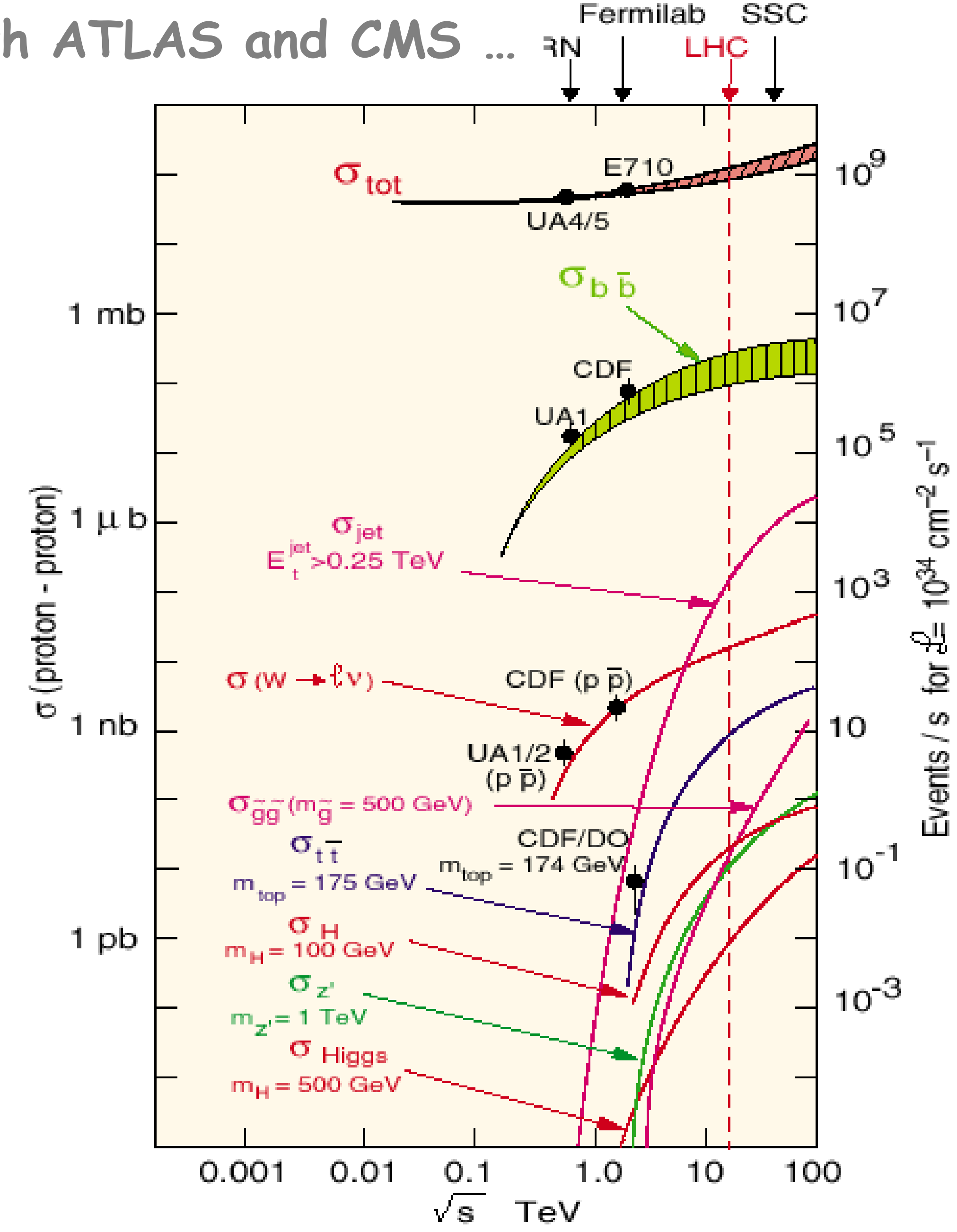
at birth (at production): $b\bar{b}$

at death (at decay): $B^0(\bar{b}d)B^0(\bar{b}d)$, i.e. $\bar{b}\bar{b}$

→ process $b \to \bar{b}$ occured

… or to discover  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 20-25 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

Passage of particles through matter

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

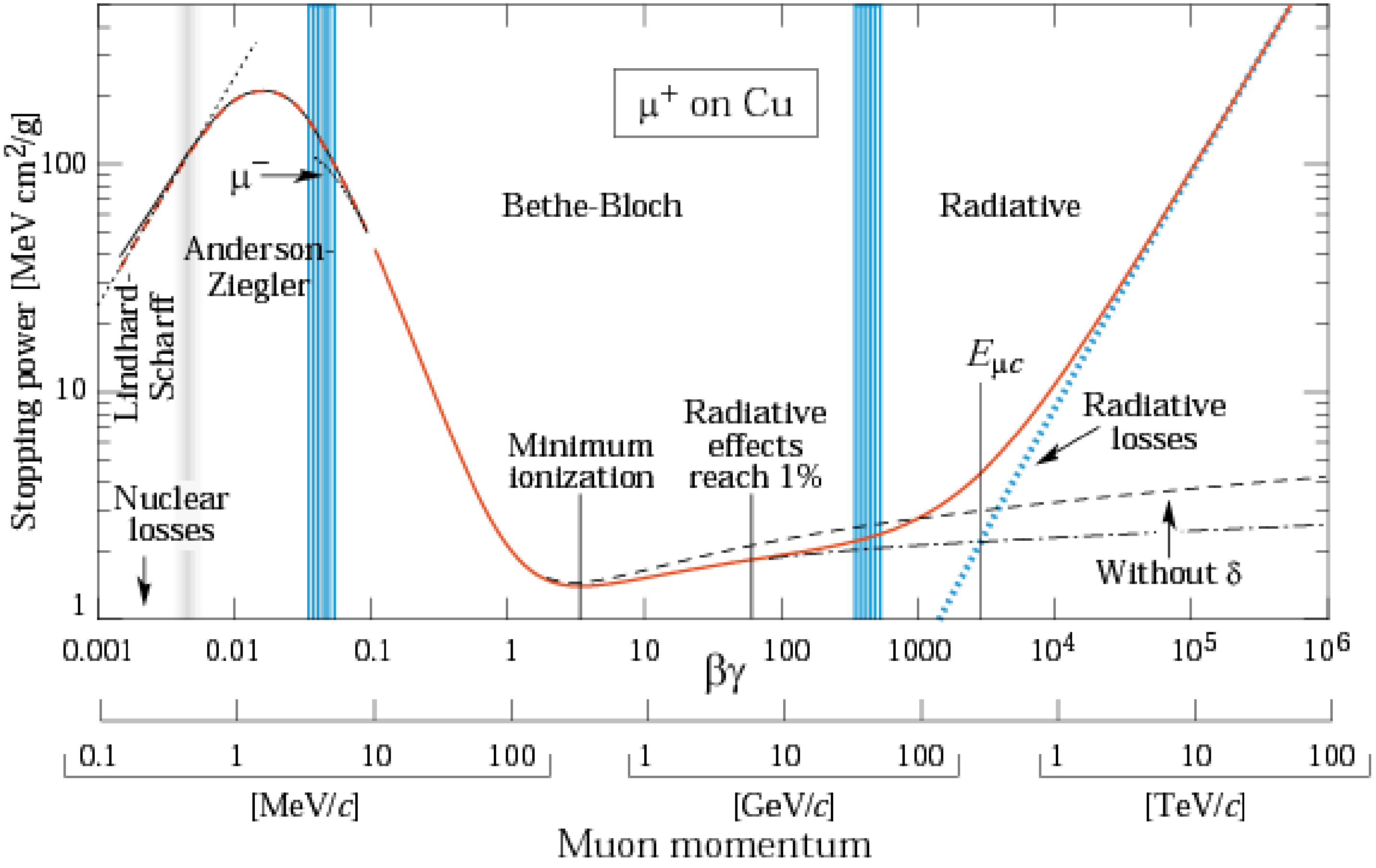
  ➔ Cherenkov or Transition radiation

  Contribute very little to the energy loss (< 5%),
  can be neglected but they are used for particle ID

Bethe-Bloch:

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

-2 C/Z
(shell correction)



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 :

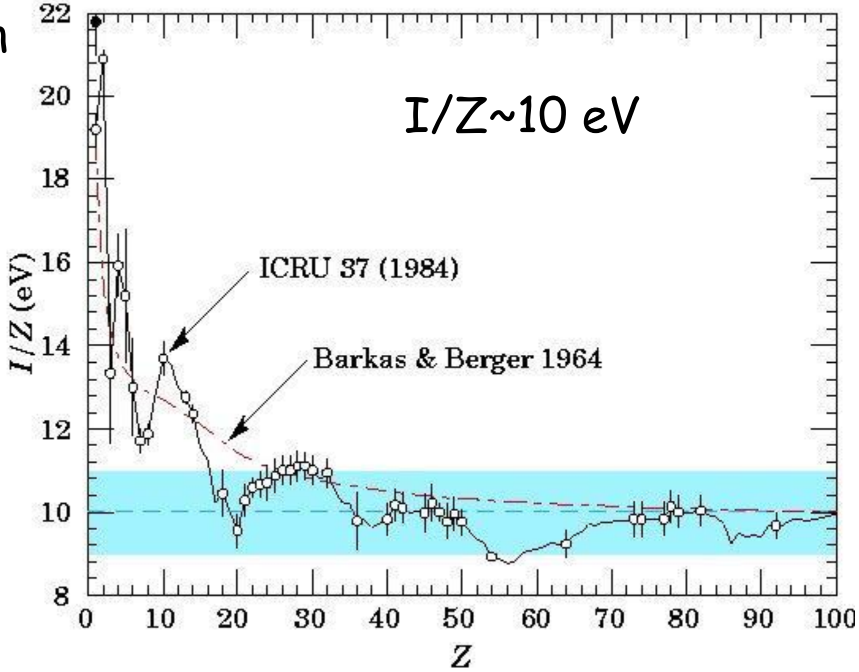
$$T_{\max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

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

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



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 correct for atomic binding. At low energy the incident particles have less chance to interact with the electronic inner orbits. For copper ~1% at $\beta\gamma=0.3$

- $0.01 < \beta < 0.05$: phenomenological fitting, Andersen and Ziegler
- $\beta < 0.01$ ("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)

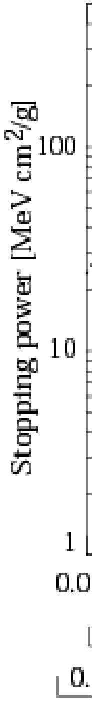
Bethe-Bloch at High energy : “density effect”

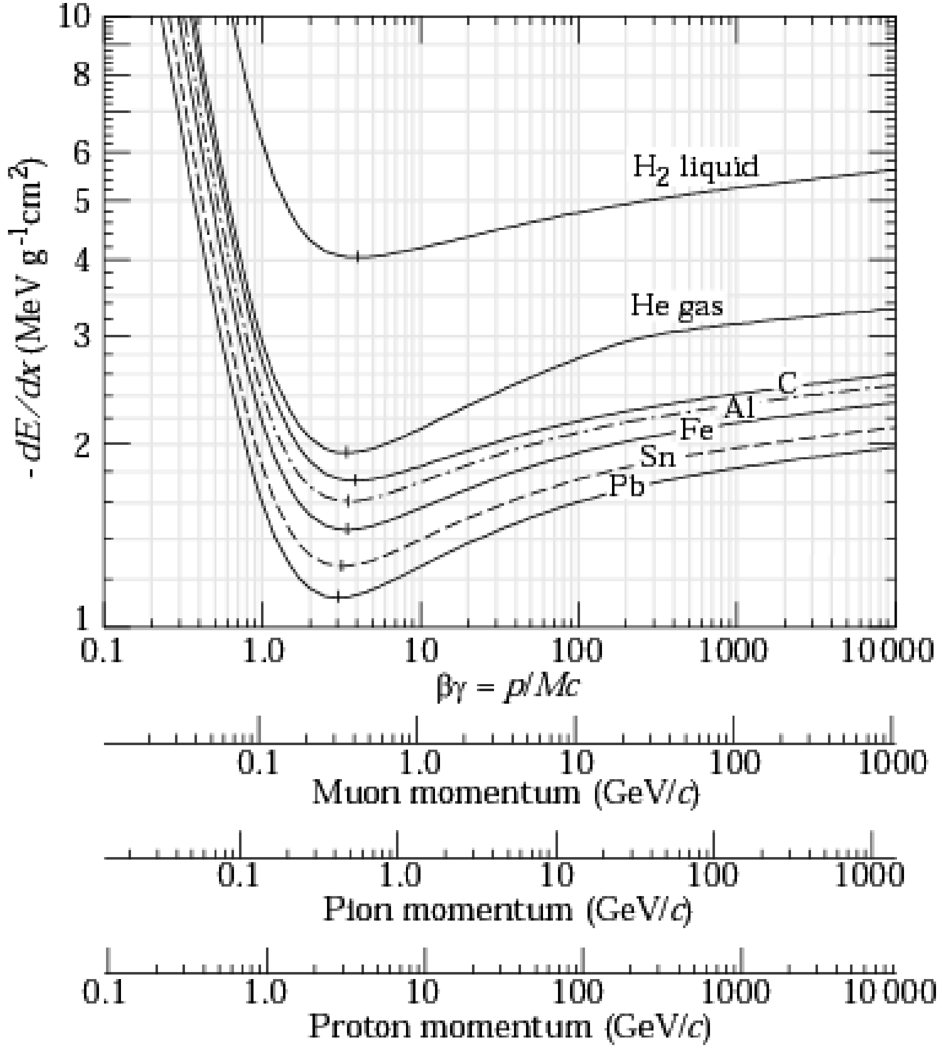
- Radiative effects become i
- Relativistic rise ~2ln$\beta\gamma$
- $\delta(\beta\gamma)/2$: charge density ef

of the atoms along incoming pa
=> screening effect
of the field, decreases
loss at high energy.

At very high energies:
$\delta/2 \to \ln(\hbar\omega_p/I)+\ln\beta\gamma-1/2$

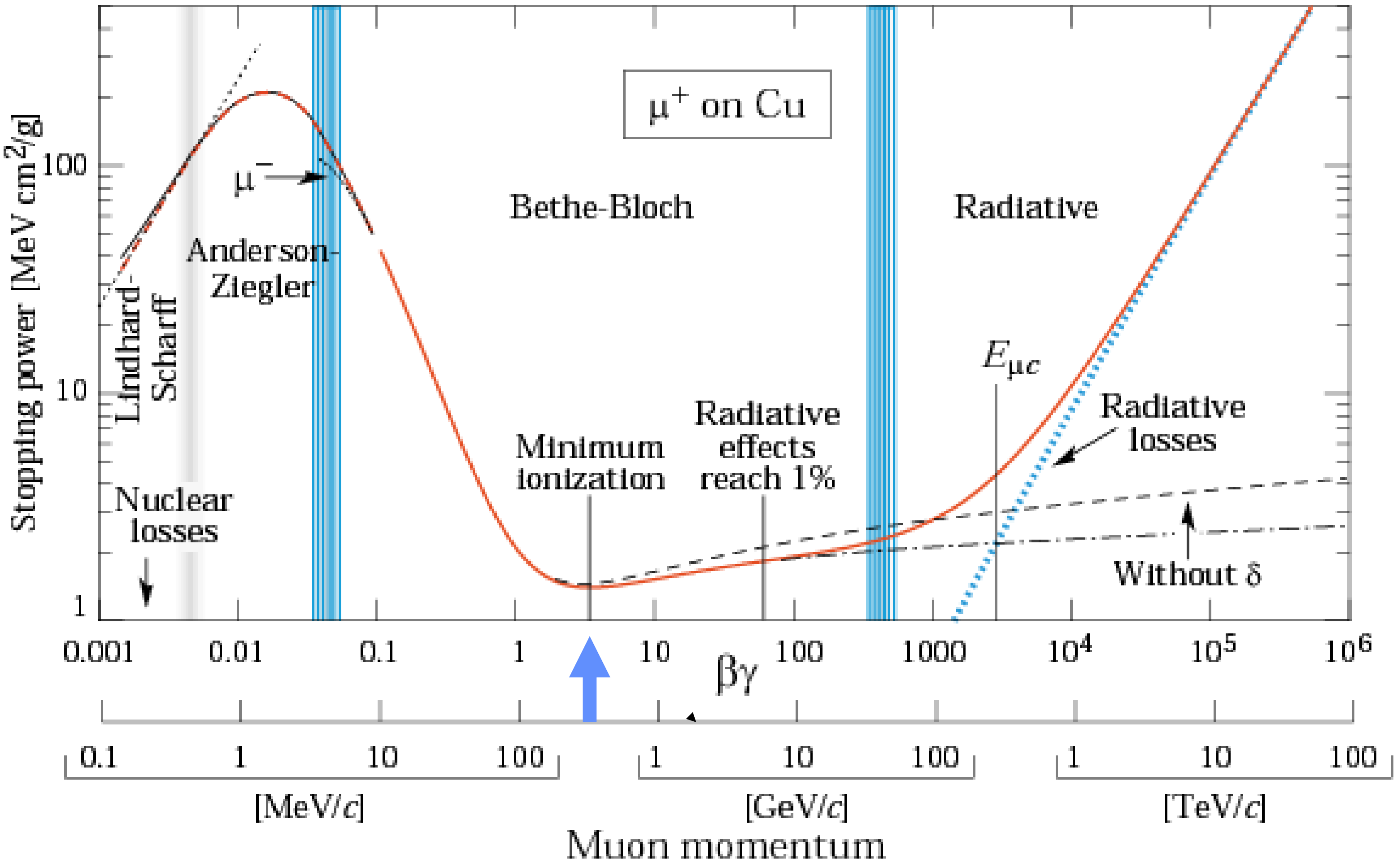
➔ Fermi plateau





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

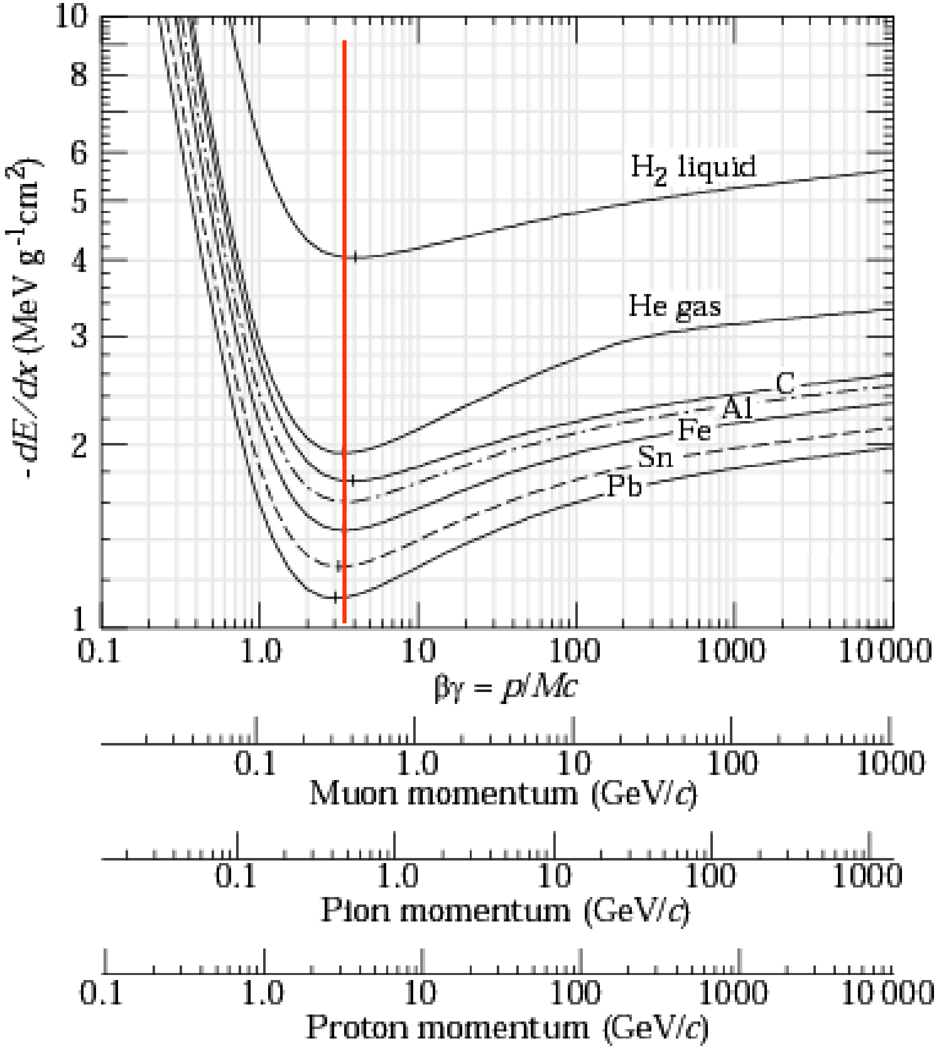
Minimum Ionizing Particle :



The minimum is approximately independent of the material

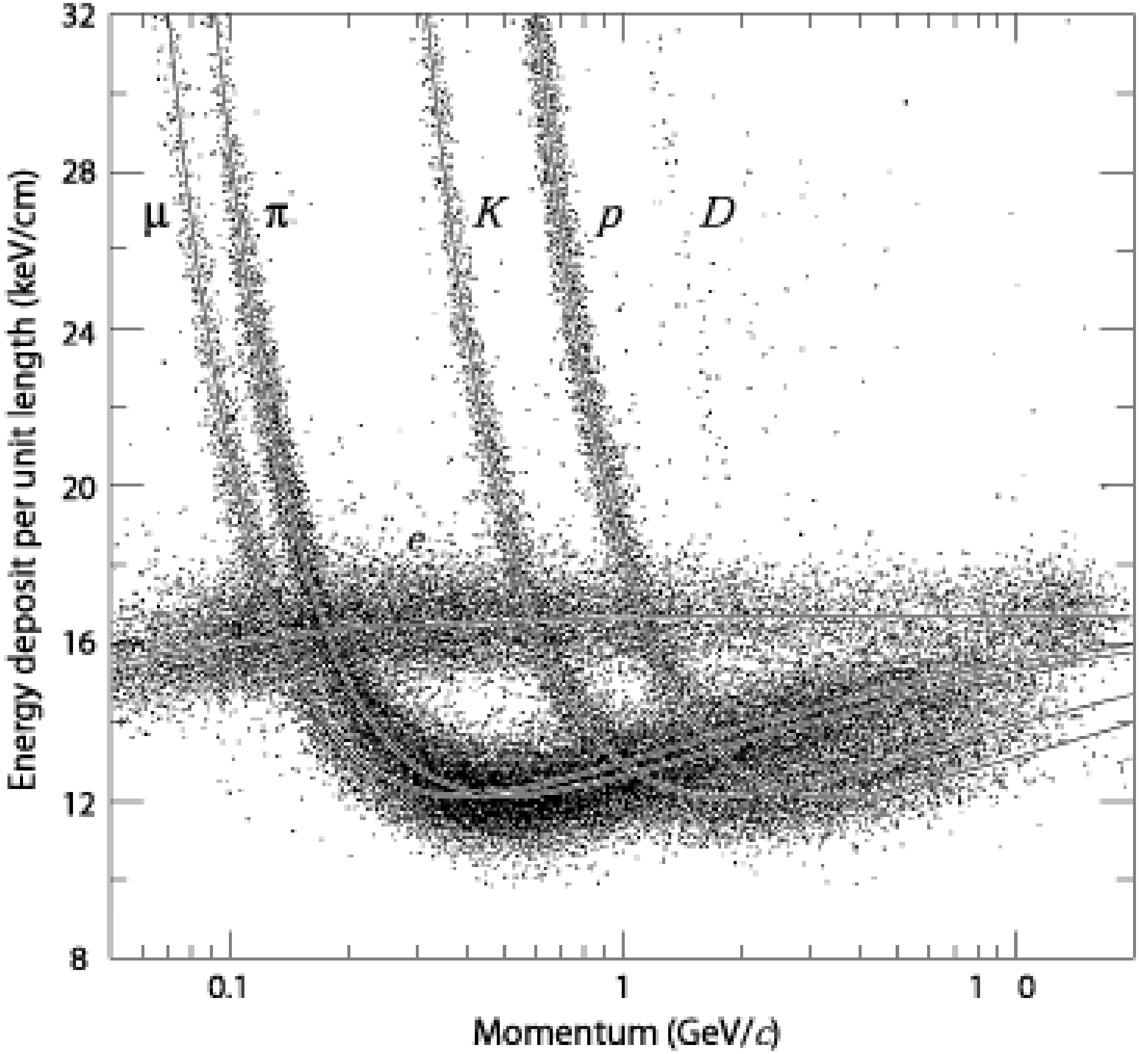
☐ Minimum at βγ ~ 3 … 4

☐ Similar for all elements
~2 MeV/(g/cm2)



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

The PEP4/9 – TPC data: dE/dx



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

Particle ID relying on d*E*/d*x* depends on p (and δp) and particle_hypothesis_1,2

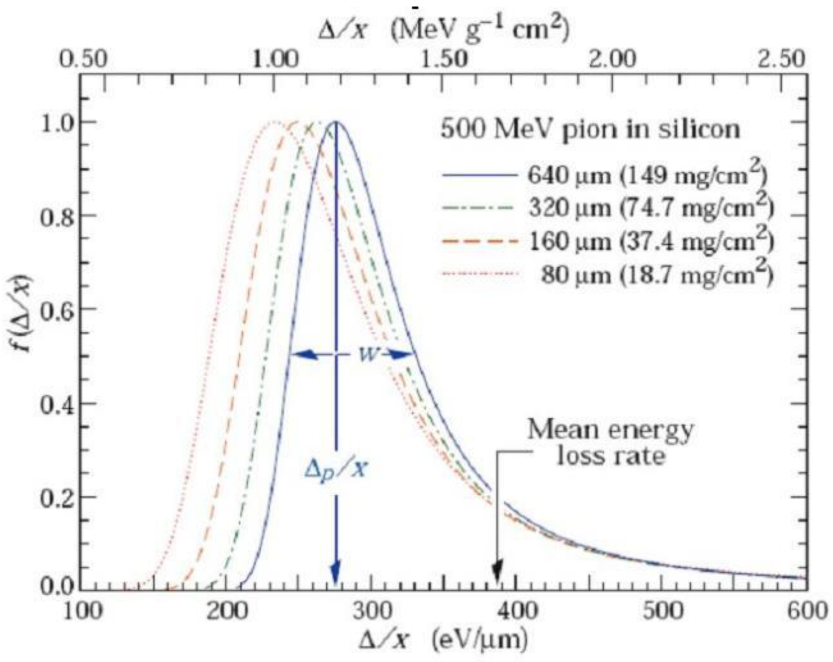
dE/dx: remarks

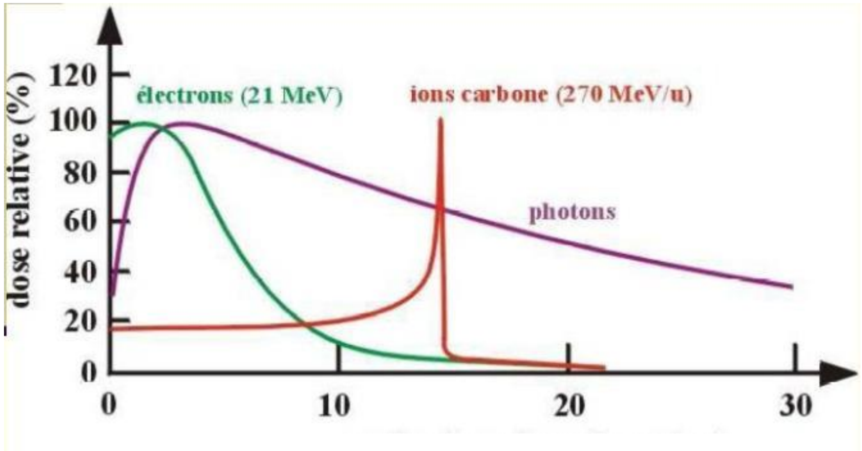
Bethe Bloch describes the average energy loss. For moderate thickness absorber fluctuations on this energy loss described by a Landau distribution. For thin absorber (small dx) fluctuations become large

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

➔ Bragg peak

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





Depth in water (cm)

dE/dx : few illustrative numbers

Energy loss of a 10 GeV muon in 1 cm of plastic scintillator ($\gamma = 1$) or a gas chamber ($\gamma = 0.001$) ?

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

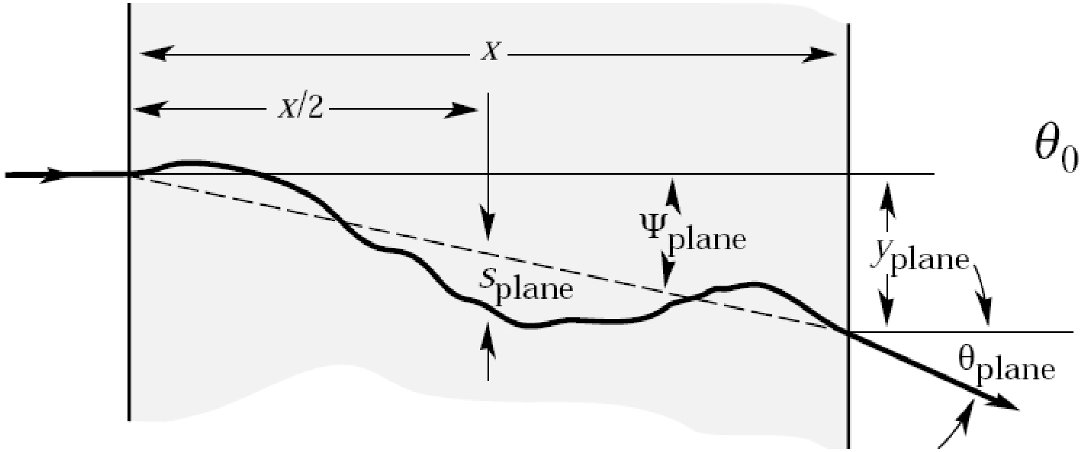
How many meters of air to stop an α particle of 2 MeV ?

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

Can stop α in 2-3 cm of air

Multiple scattering

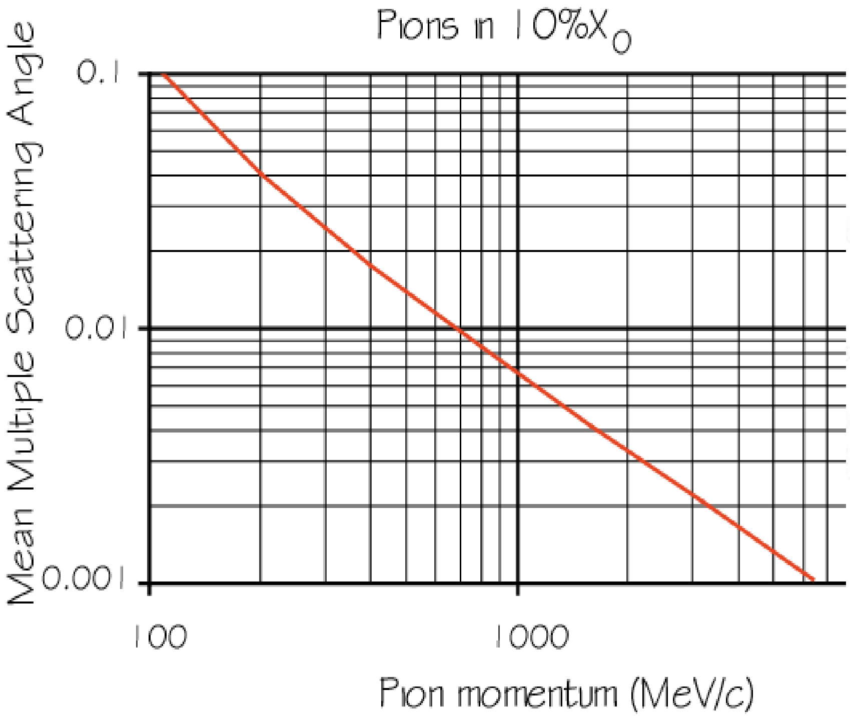
- ❑ A charged particle traversing a medium is deflected by many small-angle scatters mainly due to Coulomb scattering from nuclei → multiple scattering. Affects precision of tracking performance.

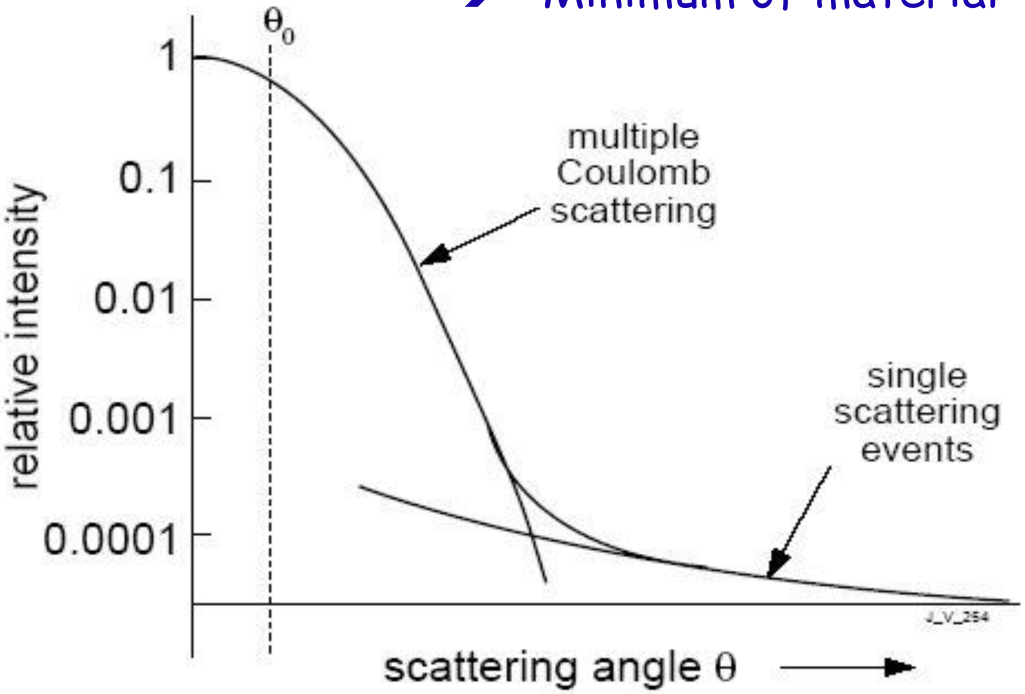


$$\theta_0 = \frac{13.6\,MeV}{\beta cp} z \sqrt{\frac{L}{X_0}}\left\{1+0.038\ln\left(\frac{L}{X_0}\right)\right\}$$

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

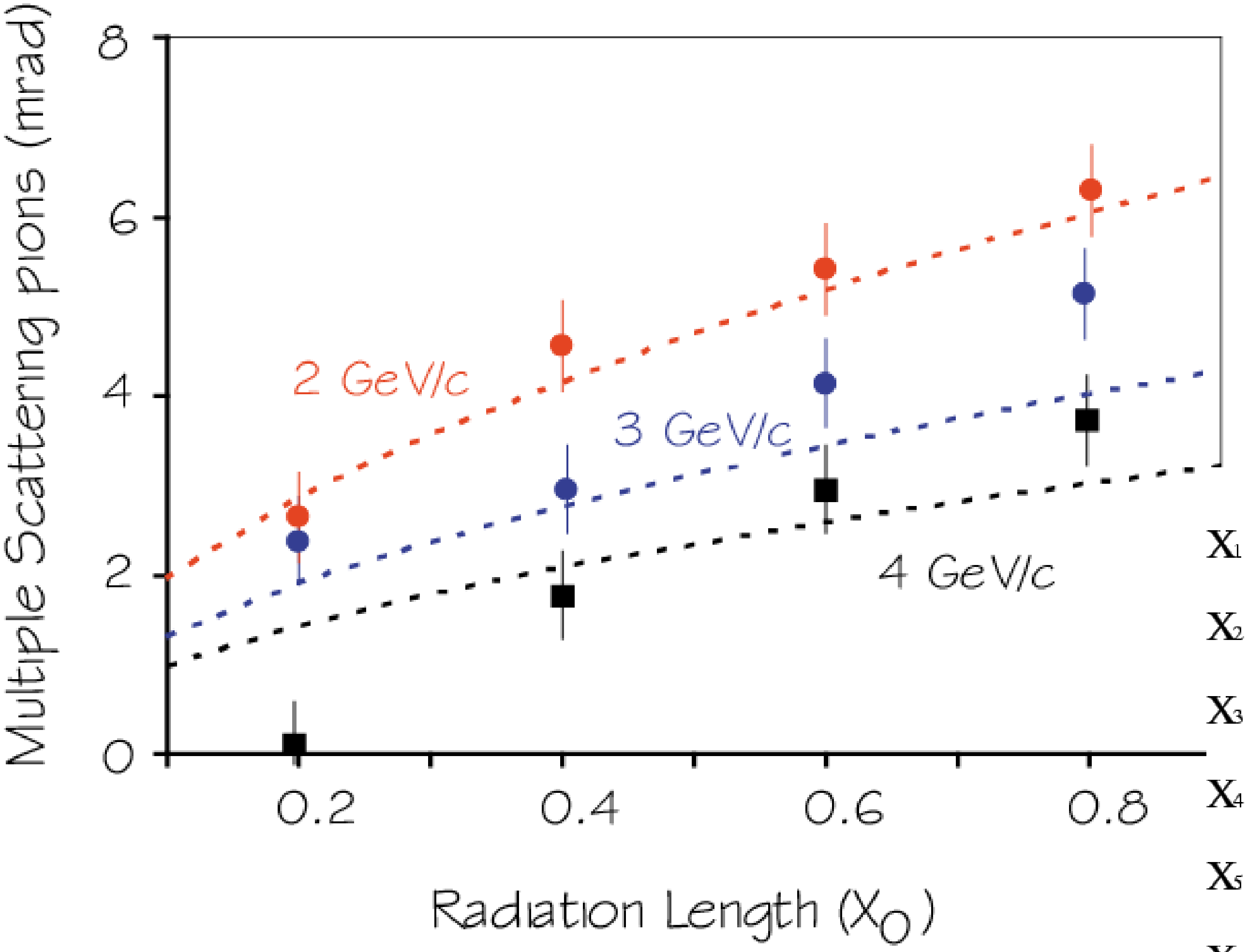
→ Minimum of material





Multiple scattering

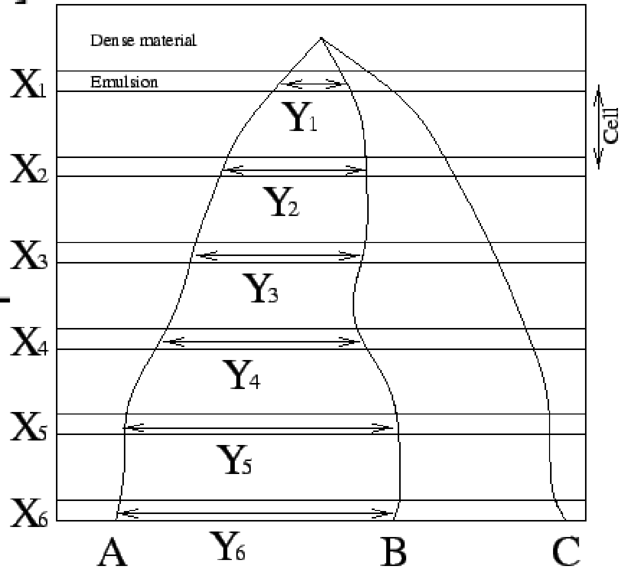
Effect of "0" if averaged for many particles, and seen as a fluctuation on a given one



OPERA

and

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



… not the best means for measuring momentum though.

dE/dx : electrons (positrons)

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

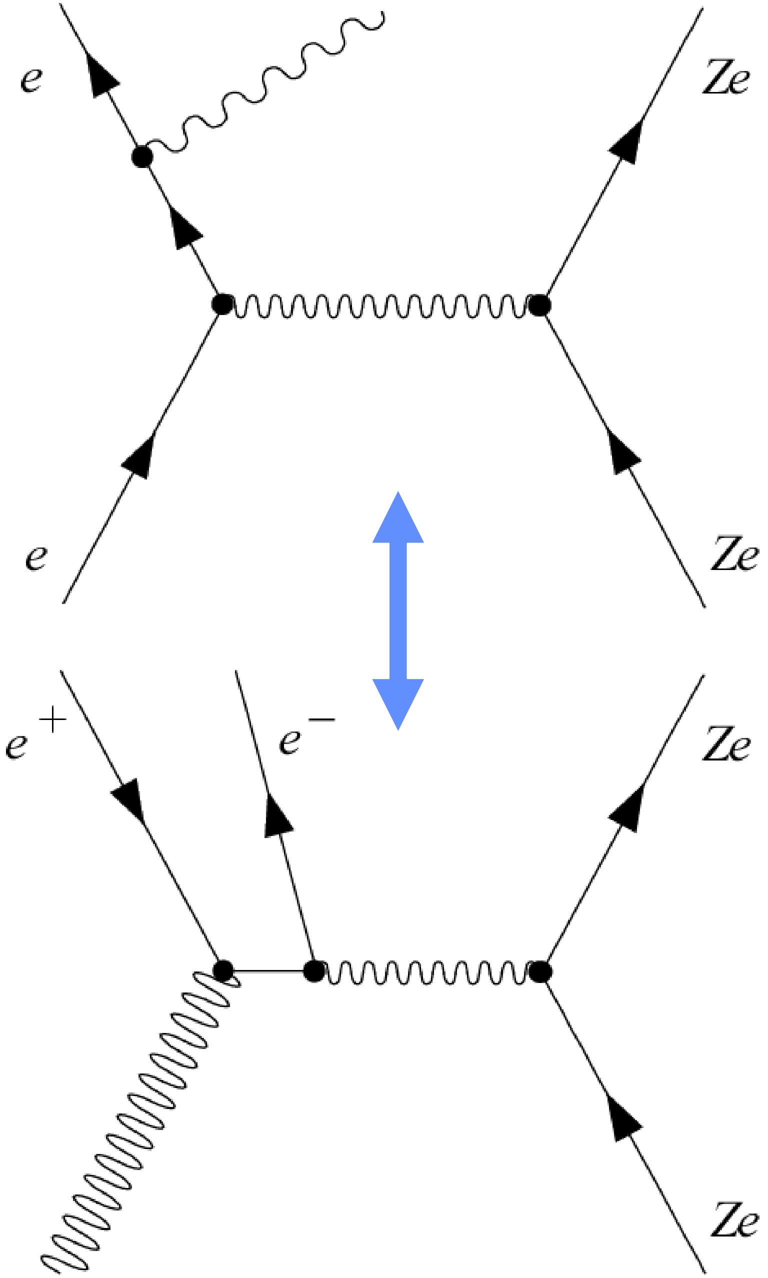
- ☐ Bremsstrahlung : emission of photon by scattering with the nucleus electrical field

  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*



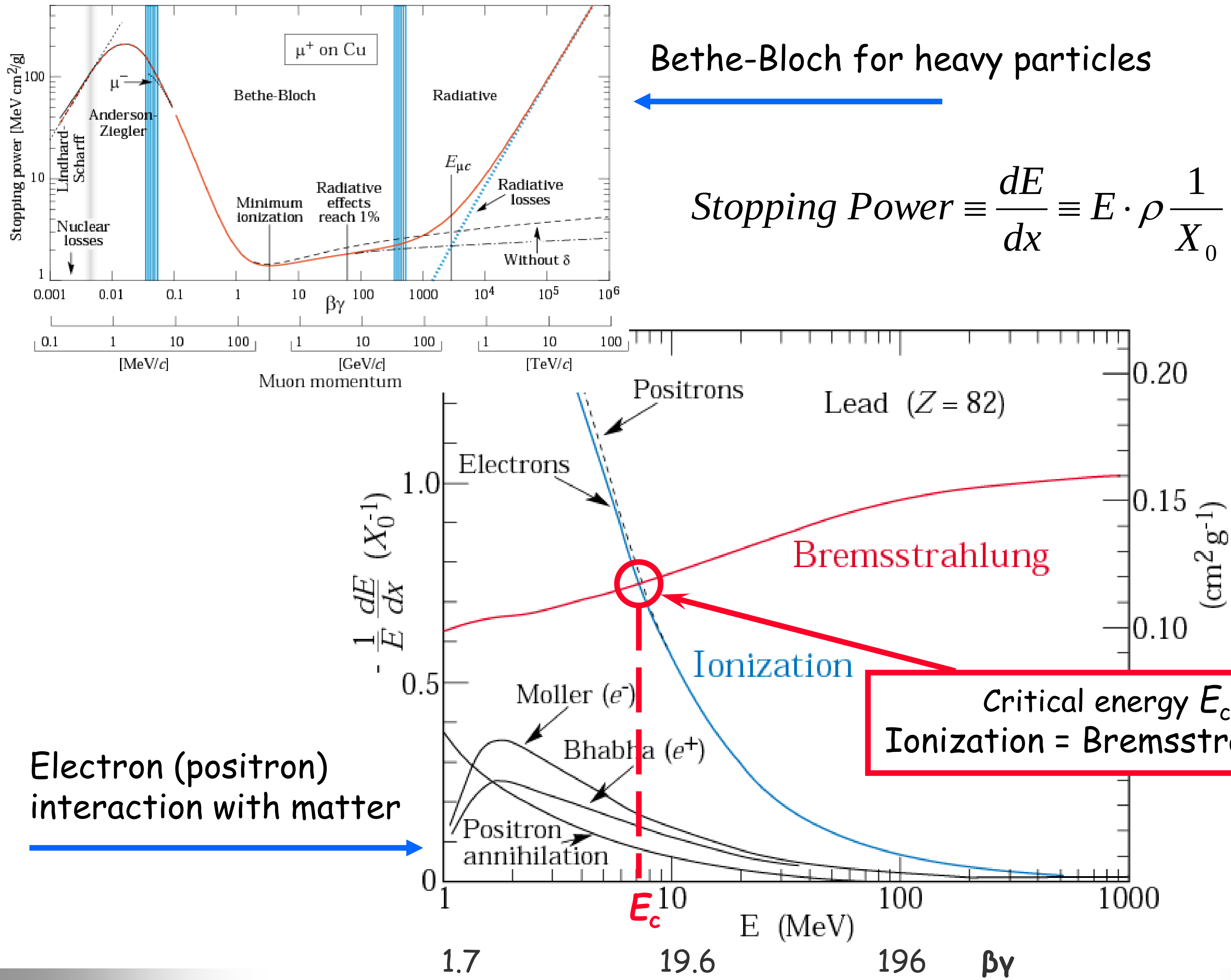
Pair production

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

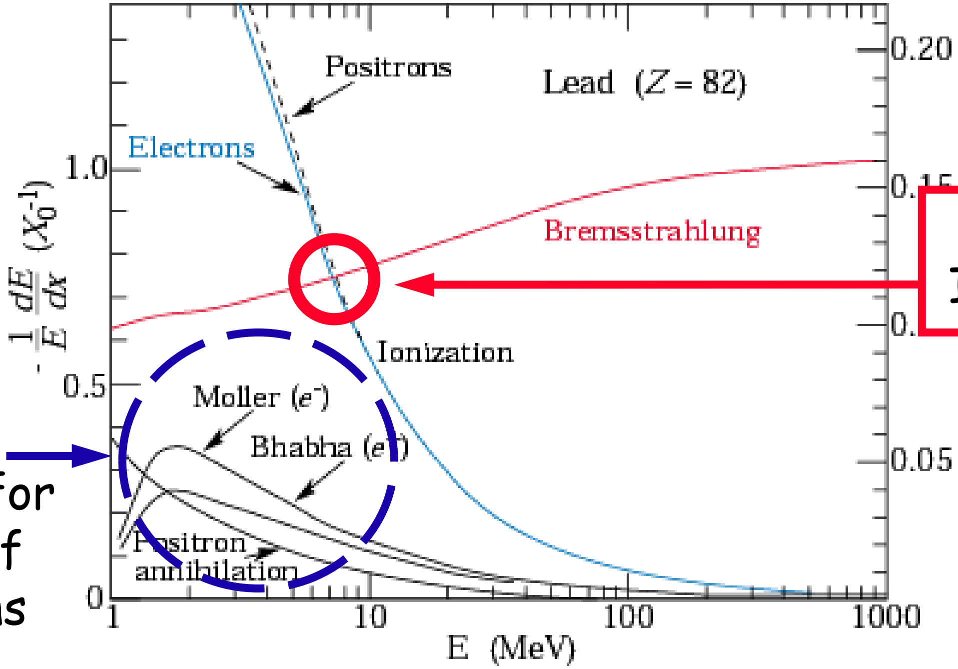
Electron (positron) interaction with matter

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



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

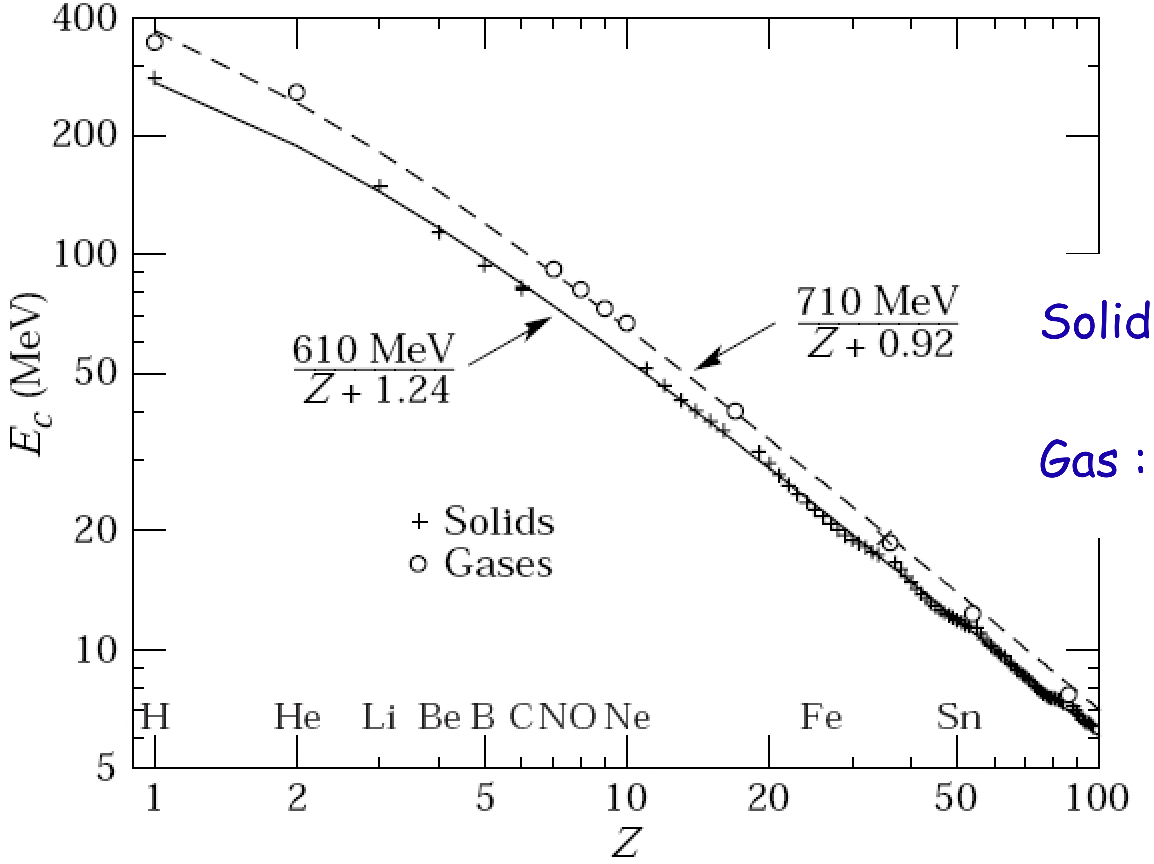


Figure 27.13: Electron critical energy for the chemical elements, using Rossi's definition [4]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

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

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

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

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

Strong dependence with Z, dominant at low photon energy

- Compton scattering

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

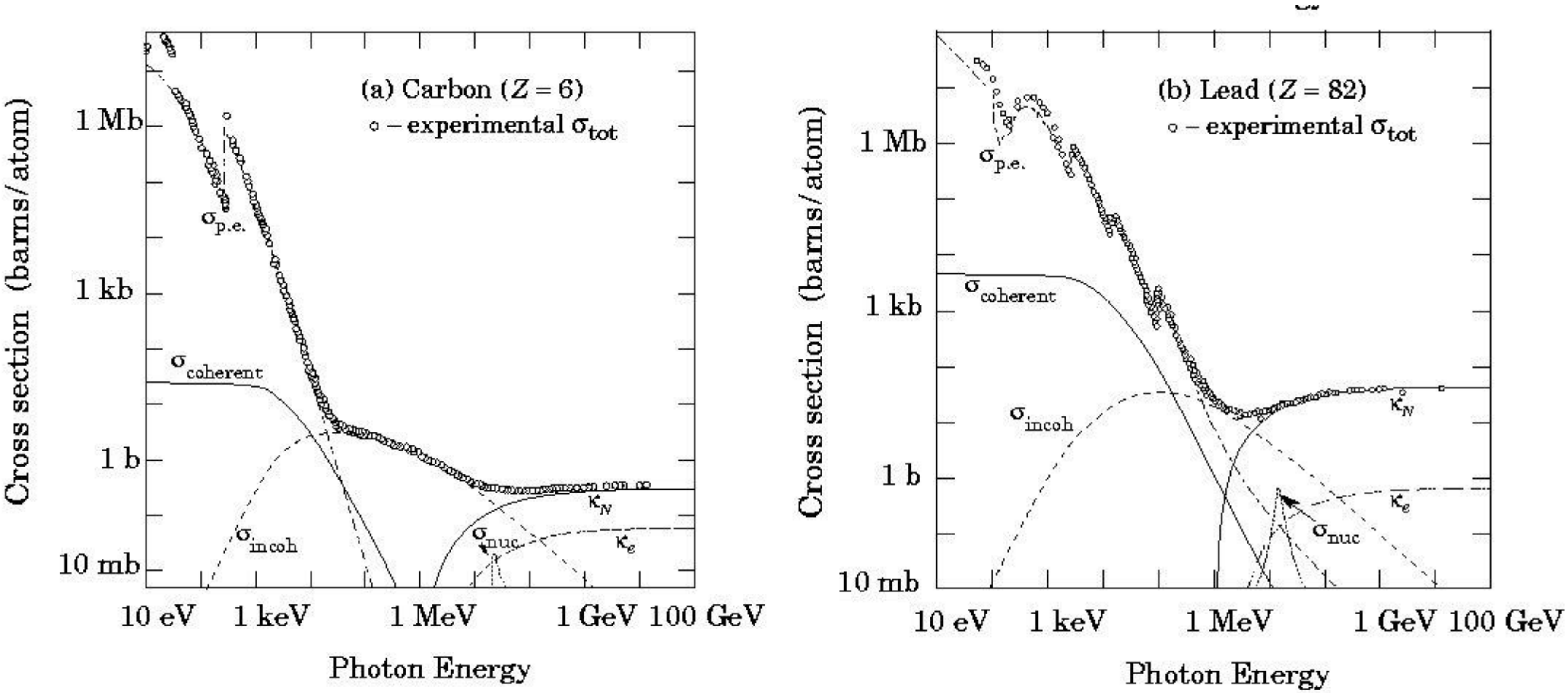
- Pair creation (similar to Bremsstrahlung) : dominant for E >> $m_e c^2$

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

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

Energy loss for photons



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

σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

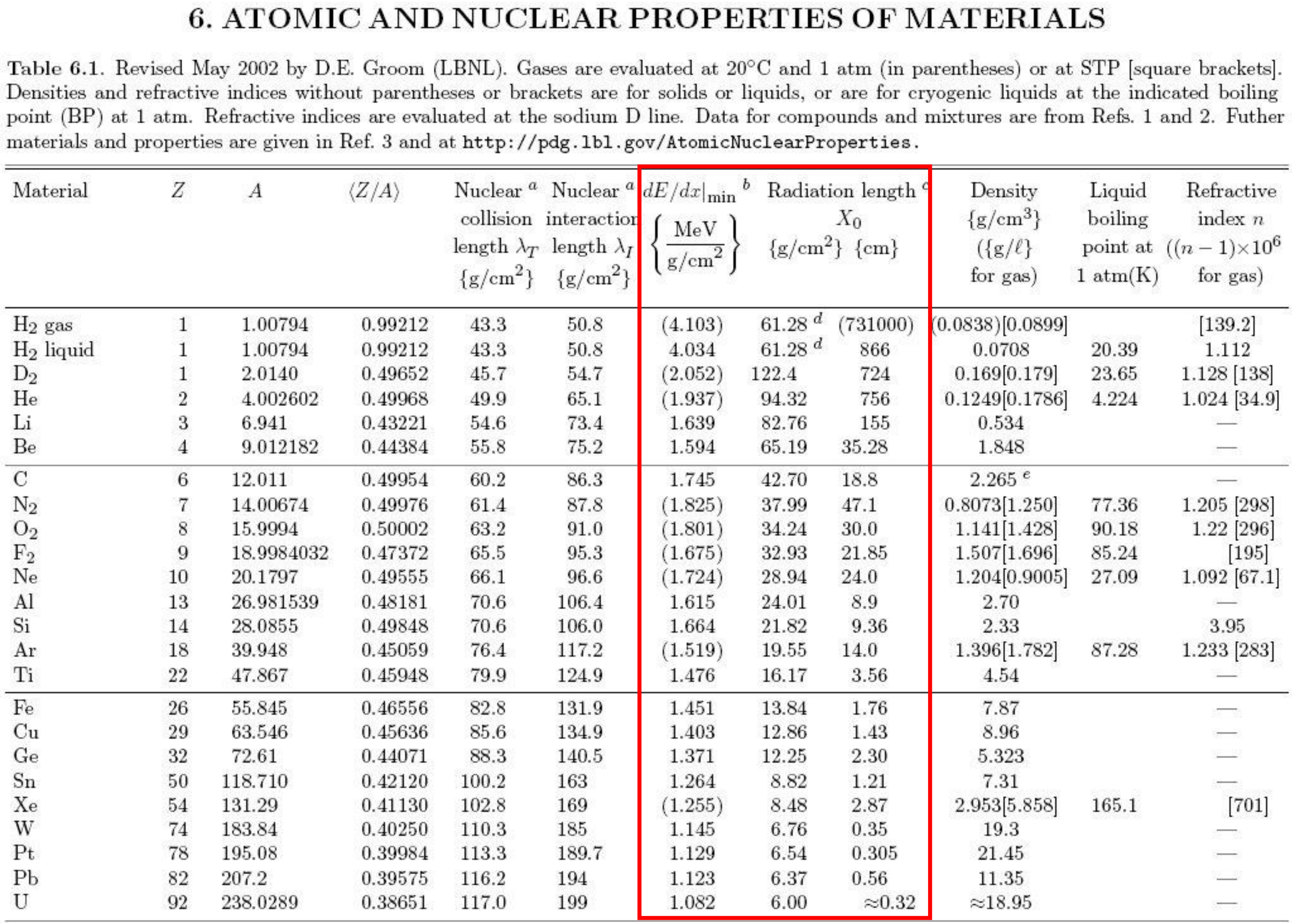
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

κ_{nuc} = Pair production, nuclear field

κ_{e} = Pair production, electron field

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

Related numbers



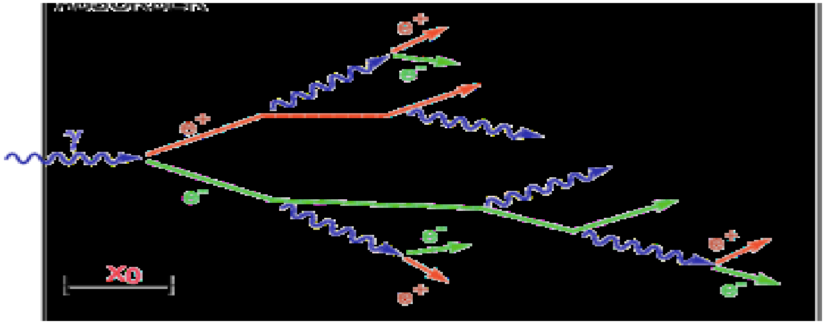
6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

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`.

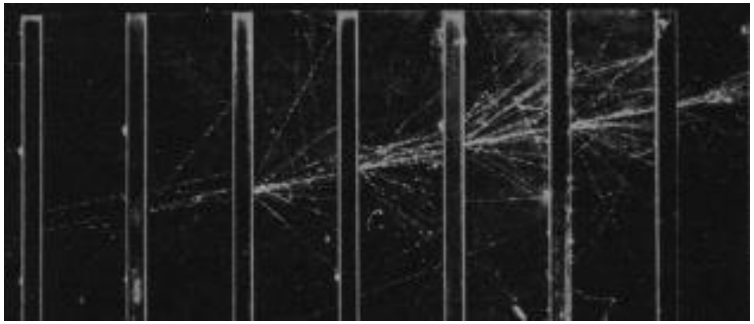
Material	Z	A	$\langle Z/A \rangle$	Nuclear[a] collision length λ_T {g/cm^2}	Nuclear[a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\min}$[b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length[c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)$\times 10^6$ 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 showers

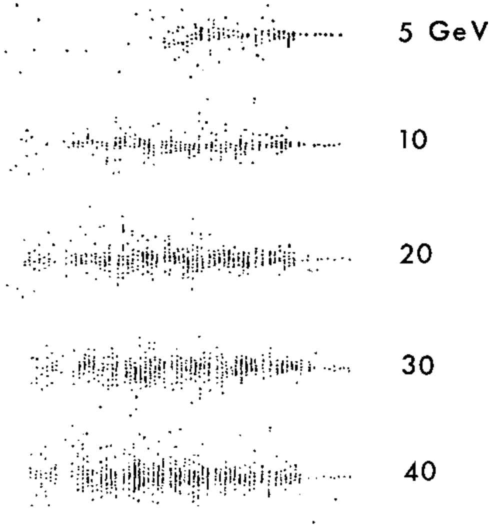
A high energy electron or photon incident on a thick absorber, initiates an EM cascade as pair production and Bremsstrahlung generate more electrons and photons with lower energy.



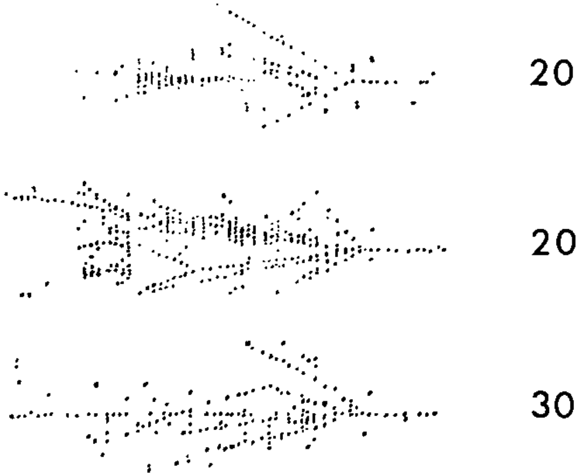
EM shower development



Lead absorbers in cloud chamber



Electron showers

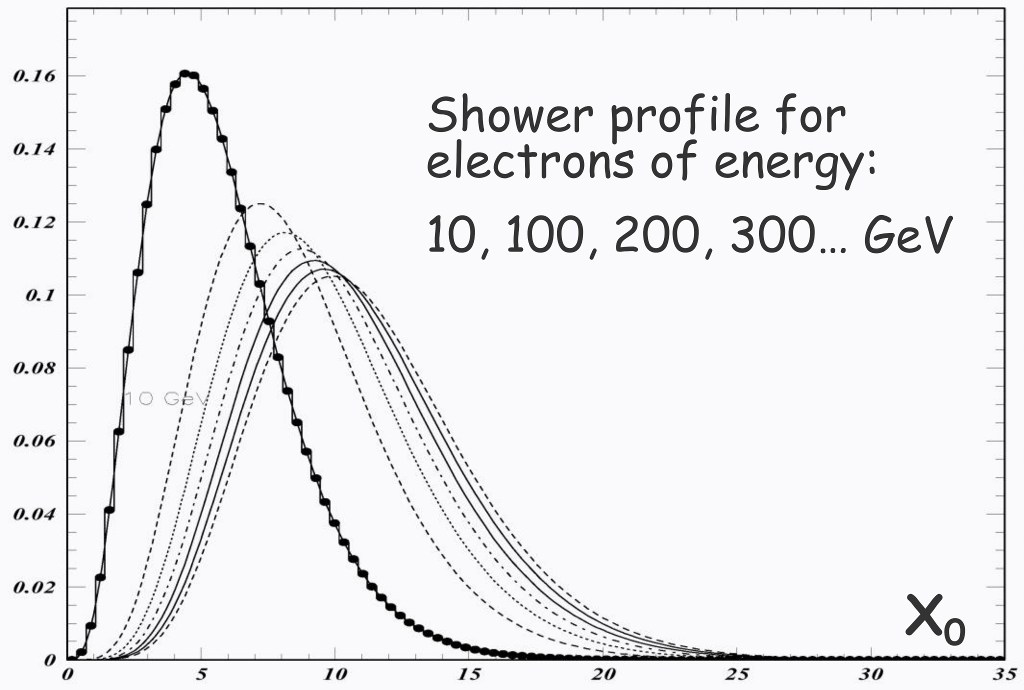


Hadron showers

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

EM showers

Longitudinal profile



Shower profile for electrons of energy:

10, 100, 200, 300… GeV

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 $1X_0$

$$R_M = \frac{21\mathrm{MeV}}{E_C} X_0 \; (Z >> 1)$$

Transverse shower containment:

75% E_0 within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

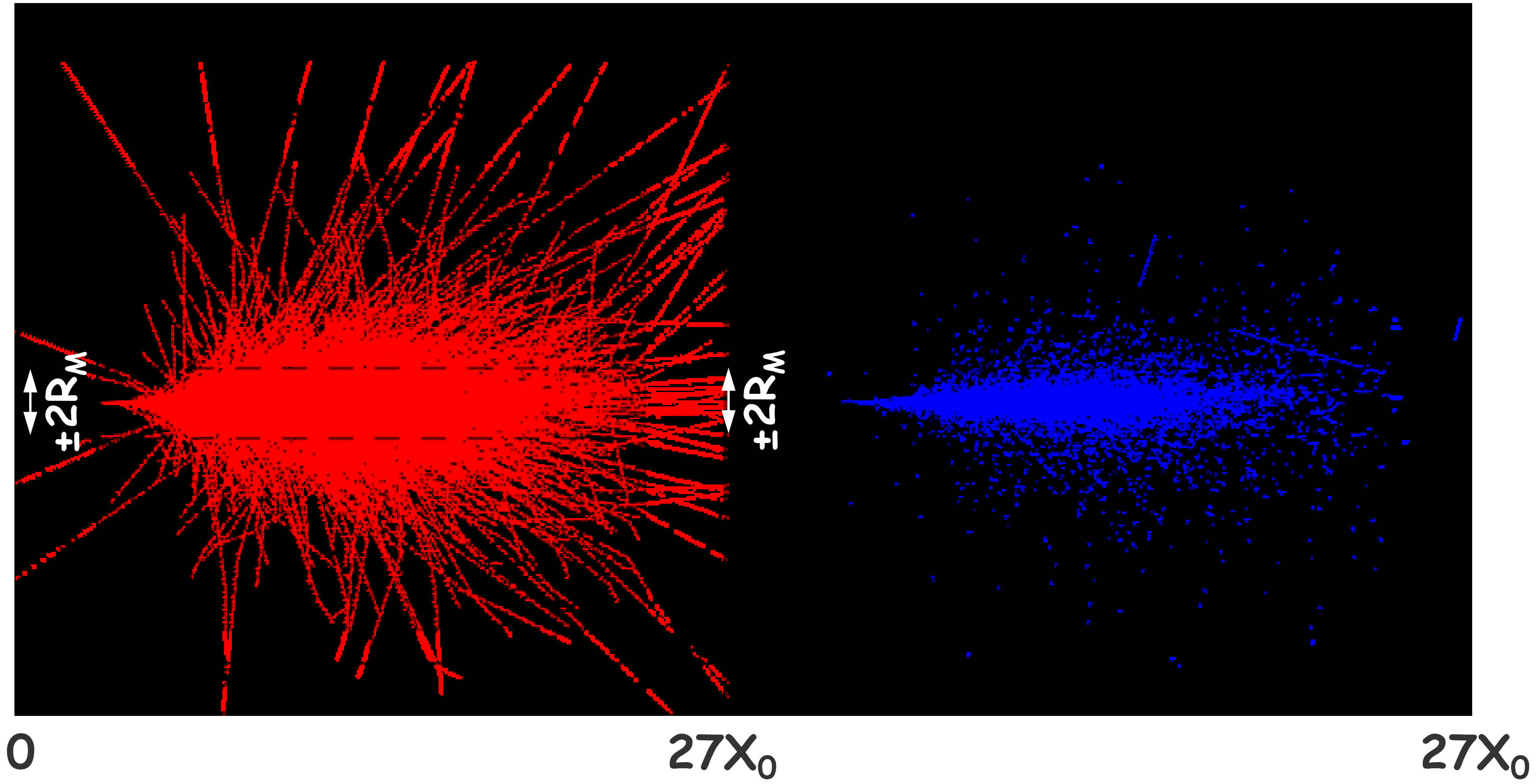
From M. Diemoz, Torino 3-02-05

EM showers

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

Photons created

Charged particles created

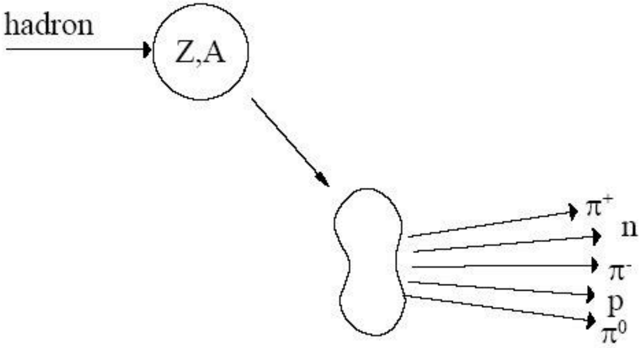


GEANT simulation: 100 GeVelectron shower in the NA48 liquid Krypton calorimeter

From D. Cockerill

Interactions of hadrons

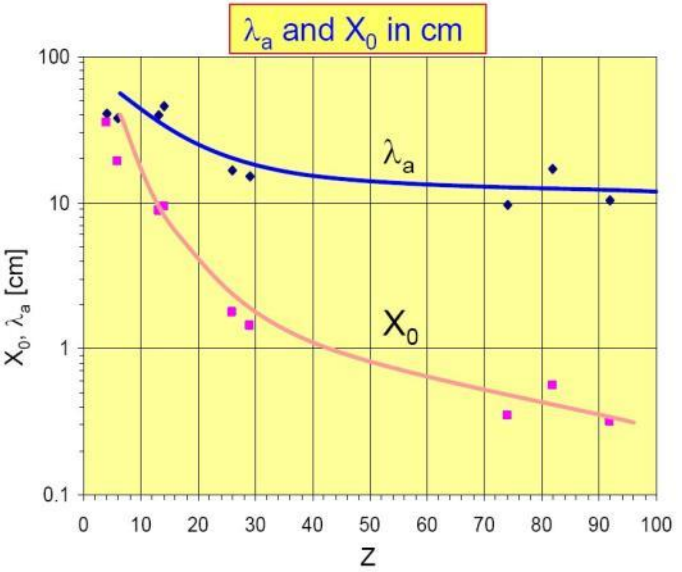
Interaction of energetic hadrons (charged/neutral) through matter involves nuclear interaction :
excitation and nucleus break up => production of secondary particles + fragment

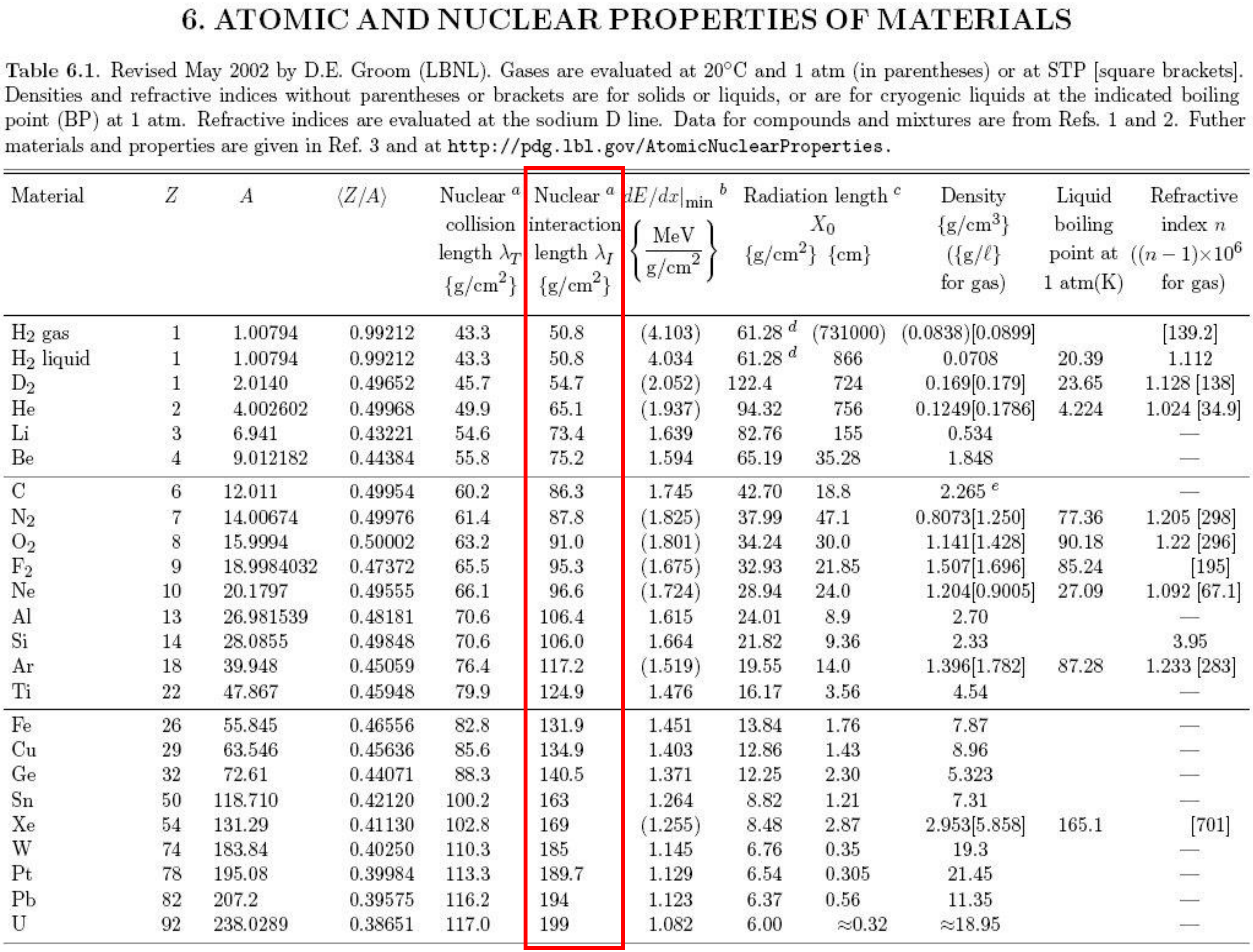


Number of particle produced ~ln (E) with average transverse p of 0.35 GeV/c

For E > 1 GeV, $\sigma \sim \sigma_0 A^{0.7}$, 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}	$dE/dx\|_{\mathrm{min}}$[b] $\left\{\frac{\mathrm{MeV}}{\mathrm{g/cm}^2}\right\}$	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 (($n-1$)×10^6 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		—

Interaction of neutron

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
  - $n + {}^6Li \rightarrow \alpha + {}^3H$, $n + {}^3He \rightarrow p + {}^3H$ $E < 20$ MeV
  - $n + p \rightarrow n + p$ $E < 1$ GeV
- Hadronic cascade for $E > 1$ GeV

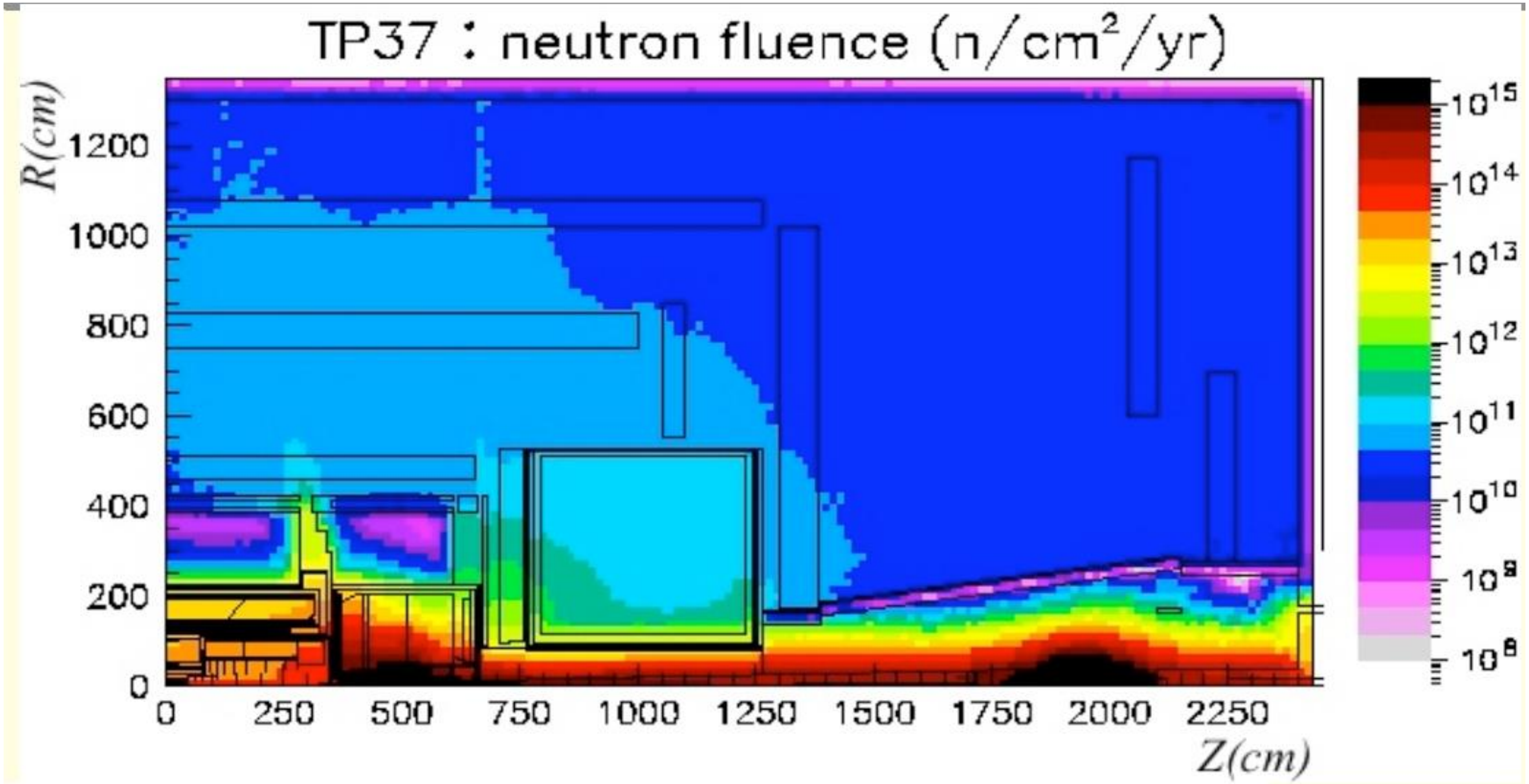
- Neutrons can travel sometimes for more than 1 μs in detectors

  ➔ outside electronics readout window

- A lot of low energy neutrons produced in LHC experiments
- Interactions in the whole cavern …

Radiation levels in ATLAS (rad/year)

L. Serin



At r=11 cm, photons flux of 30 MRad !

100 Rad ~ 6.2410^{12} MeV/kg deposited energy (1J/kg)

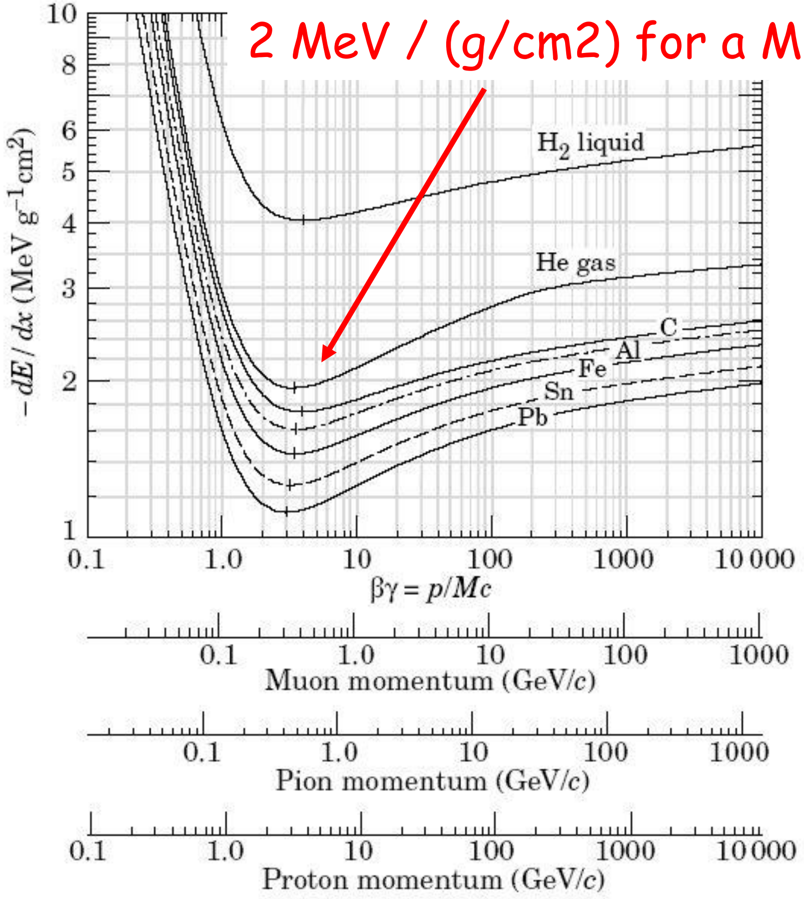
Strong constraint on detector technology and electronics : ageing in gaseous detectors light loss (transparency) in scintillators/cerenkov, atom displacement in solid detectors

Interaction of neutrinos

- Only weak interaction
- $\nu + n \rightarrow l^- + p$ or anti $\nu + p \rightarrow l^+ + n$ ➔ 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

Summary of interaction of particles with matter

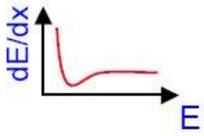
Bethe-Bloch for heavy charged particles


2 MeV / (g/cm2) for a MIP

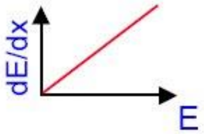
Radiation length X_0

e^+ / e^-

- Ionisation

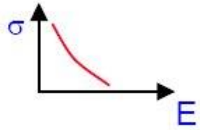


- Bremsstrahlung

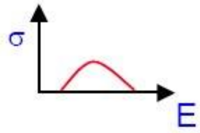


γ

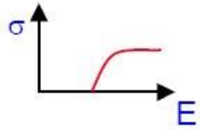
- Photoelectric effect



- Compton effect



- Pair production



Interaction of hadrons : many different particles produced,

interaction length λ_I

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

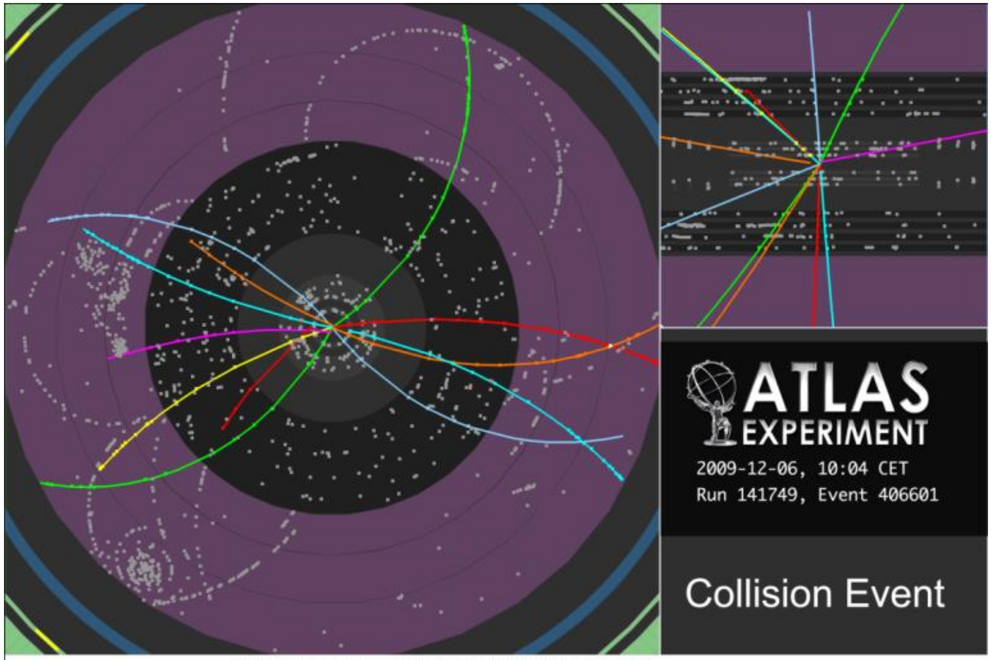
… but let us first look through common methods and tools

Non-destructive methods: charged particles → tracking

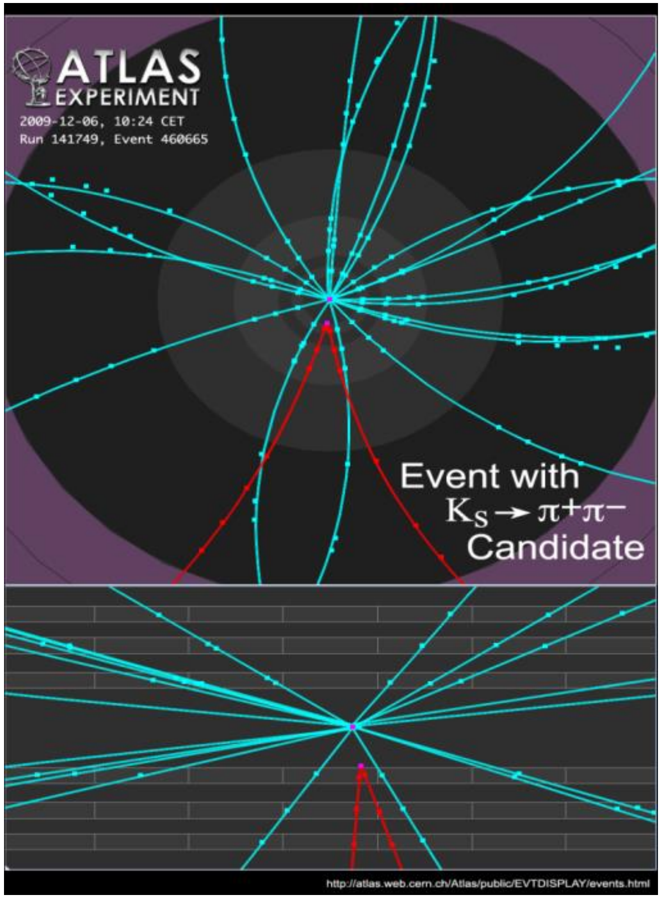
Gaseous detectors

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



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

$K_S \rightarrow \pi^+\pi^-$ candidate as reconstructed in the Inner Tracker

Silicon detectors

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

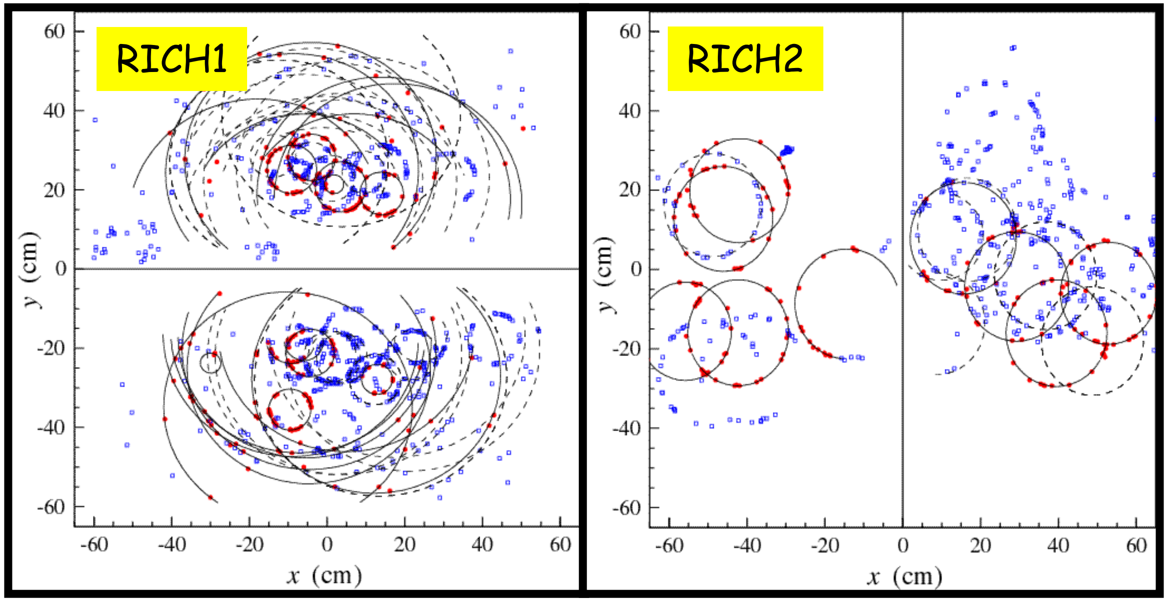
Non-destructive methods: charged particles → particle ID

Cherenkov detectors

Measure: Cherenkov radiation angle (threshold)
→ Particle ID

Radiator
+ Cherenkov light measurement
+ …

Example: LHCb Ring Imaging CHerenkov detector RICH



- + Transition radiation detectors
- + dE/dx from tracking detectors
- + Time-Of-Flight
- + …

Destructive methods

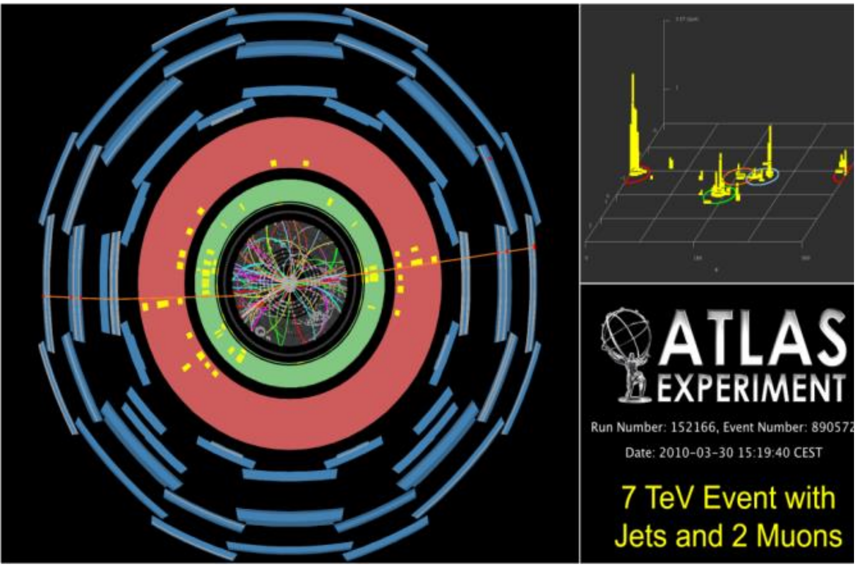
Calorimeters: electromagnetic and hadronic

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

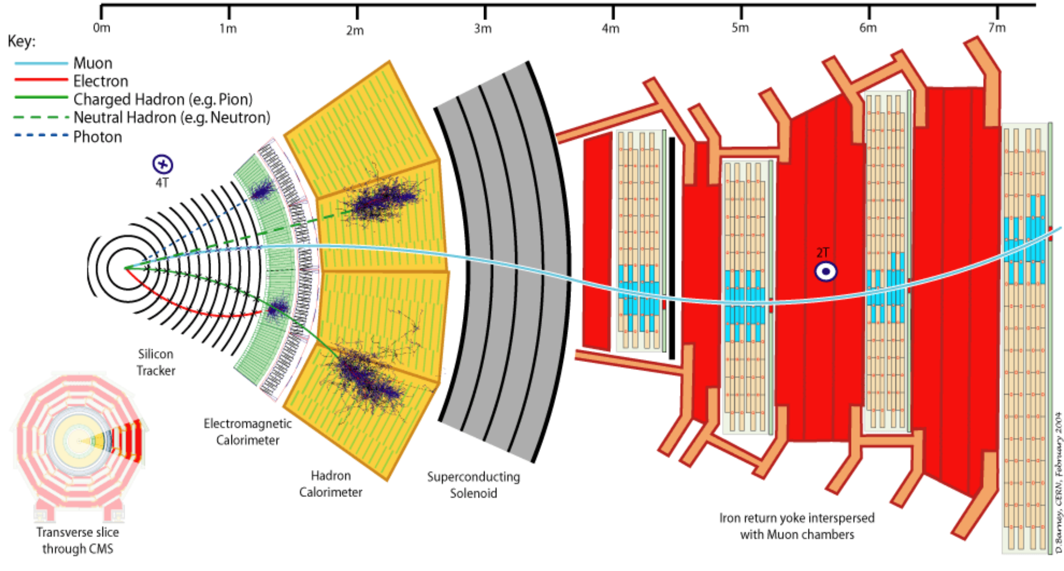
Muon detectors

Measure: Muon track after absorber
➔ Particle ID

Muons in ATLAS



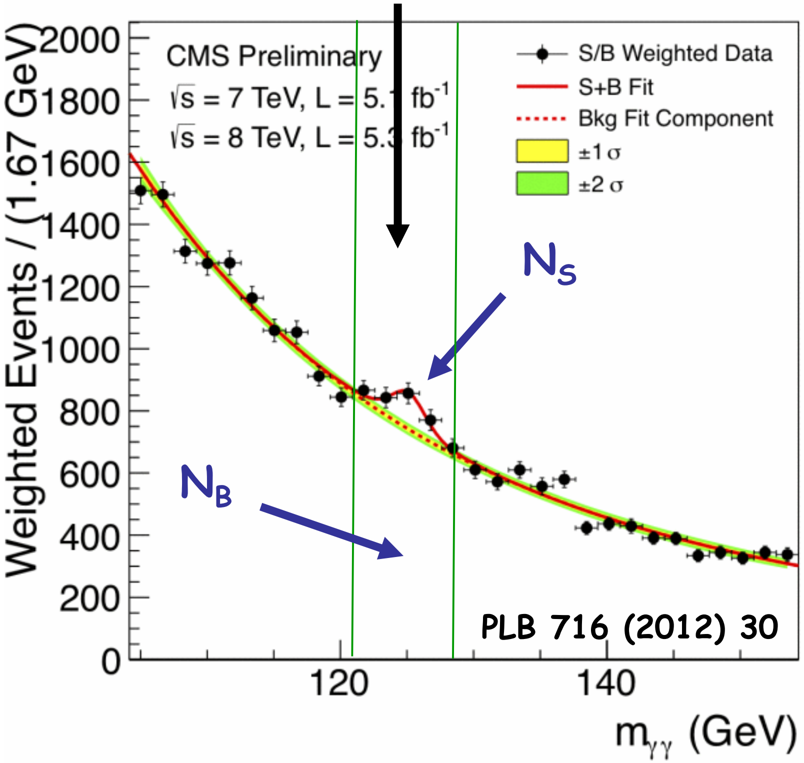
Muon in CMS



Criteria: efficiency and resolution

- **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 ?



PLB 716 (2012) 30

Statistical significance : $S = N_S / \sqrt{N_B}$

N_S (N_B) : Number of signal (background) events, estimated in the peak region

→ *Lecture and practical work by Yonas*

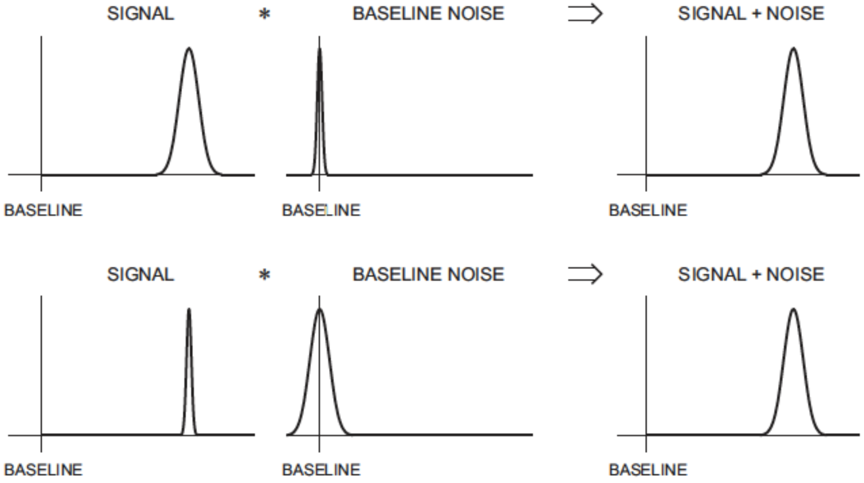
$$S \sim \varepsilon \sqrt{L / \sigma}$$

- S > 5 → signal > 5 times higher than the expected fluctuation on N_B
- Probability, that the background fluctuates by more than 5σ is 10^{-7}

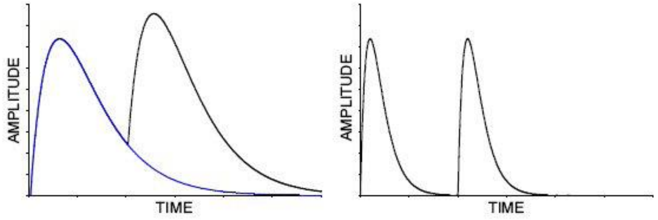
→ **Discovery**

Criteria: efficiency and resolution

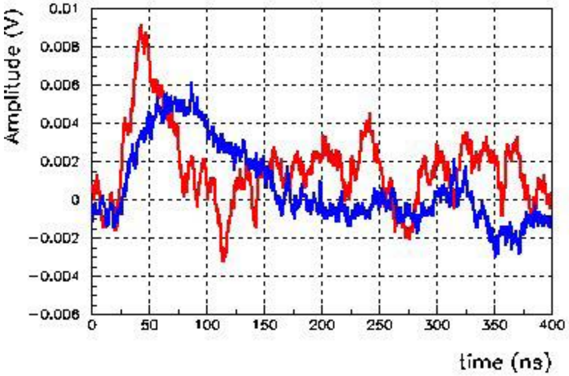
- **Signal treatment** added to intrinsic detector resolution → **Read-out electronics** !
  - Every signal comes with its noise



  - Reduce pile-up

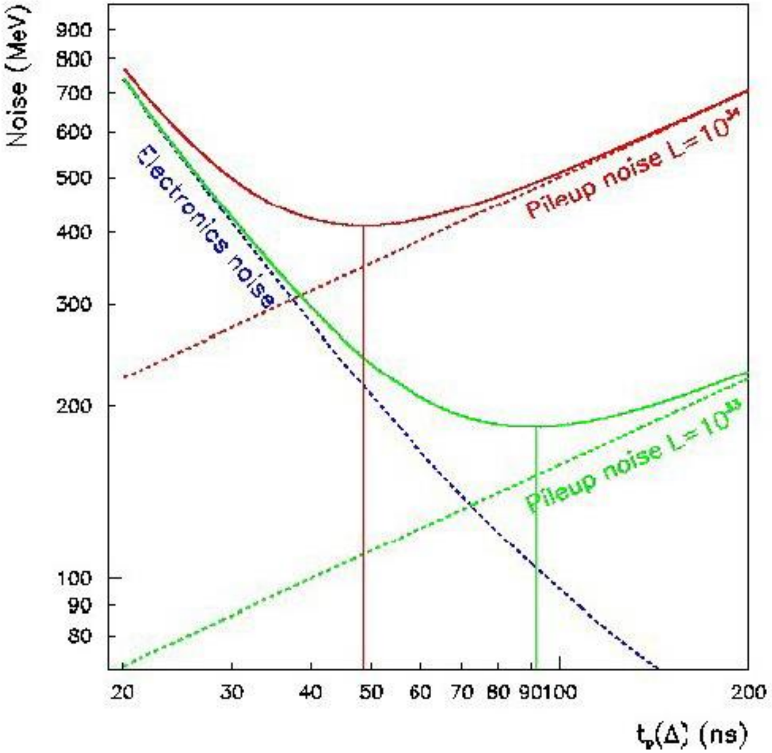


  - Realistic signal + noise shape



After E. Garutti et al.

- 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



Q1

Silicon detectors ➔ Position resolution: ~ 5 μm

Gaseous detectors ➔ Position resolution: ~ 50 μm

Calorimeters ➔ Position resolution: few mm

Why calorimeters are very important for position measurements ?

Q2

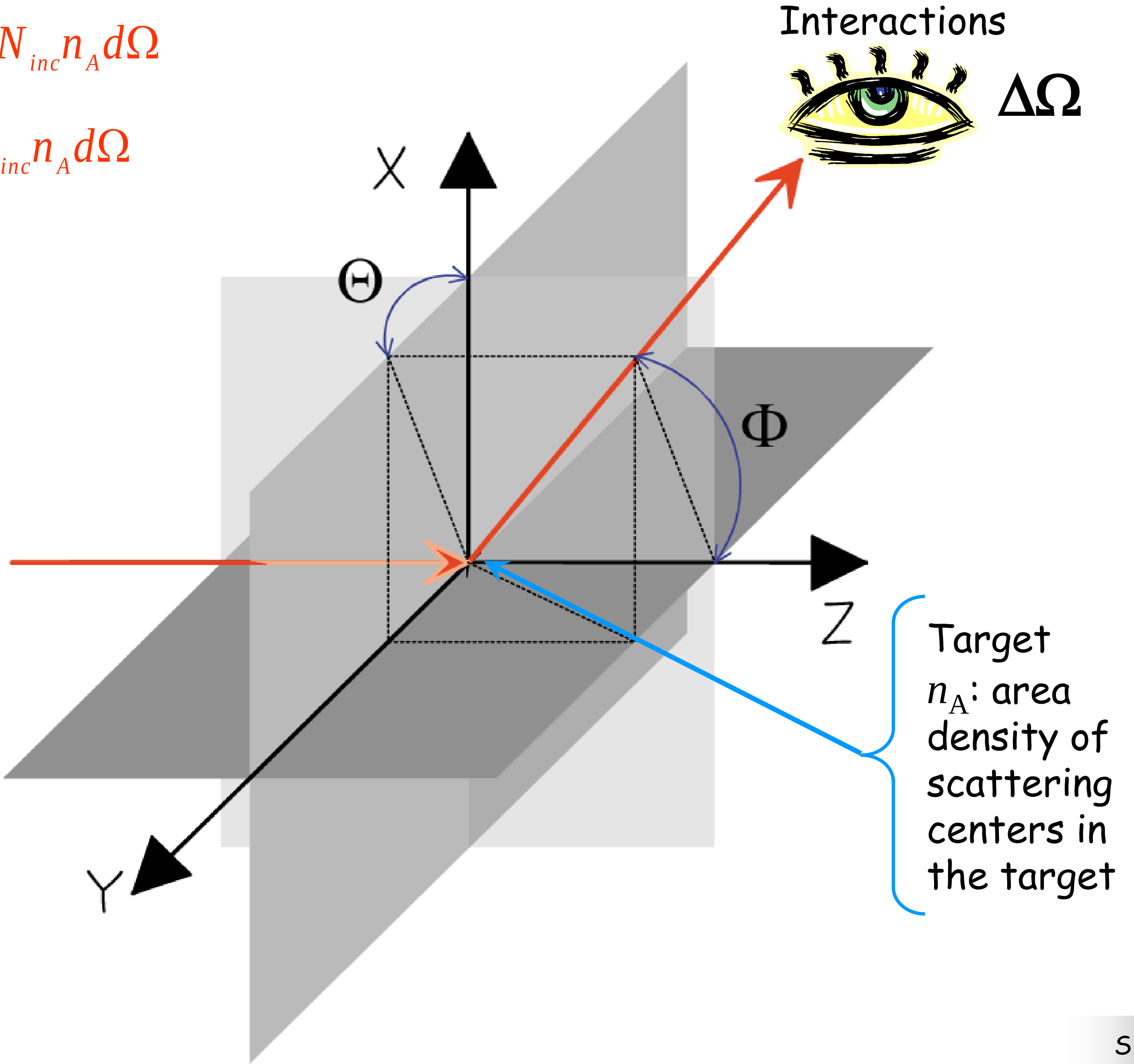
Two electromagnetic showers are initiated by an electron and by a photon.

Which shower will penetrate deeper in the calorimeter ?

Some units and conventions

$$N_{scat}(\Theta,\Phi) \propto N_{inc} n_A d\Omega$$

$$= \frac{d\sigma}{d\Omega(\Theta,\Phi)} N_{inc} n_A d\Omega$$



Target
n_A: area density of scattering centers in the target