Detektory do fizyki wysokich energii

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

Usual disclaimers:
Selective and biased introduction by a particle physicist
Many simplifications, avoid formalism
Slides of many colleagues used without proper references

Bezmiechowa Górna, 11-20/07/2024

Some units and conventions

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

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

energy $\boldsymbol{E}$: measured in **eV**
momentum $\boldsymbol{p}$: measured in eV/c or **eV**
mass $\boldsymbol{m_0}$: measured in eV/c^2 or **eV**

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

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

1 eV is a small energy.
1 eV = $1.6 \cdot 10^{-19}$ J
$\boldsymbol{m}_{\mathbf{bee}}$ = 1g = $5.8 \cdot 10^{32}$ eV
$\boldsymbol{v}_{\mathbf{bee}}$ = 1 m/s => E_{bee} = 10^{-3} J = $6.25 \cdot 10^{15}$ eV
$\boldsymbol{E}_{\mathbf{LHC}}$ = $14 \cdot 10^{12}$ eV

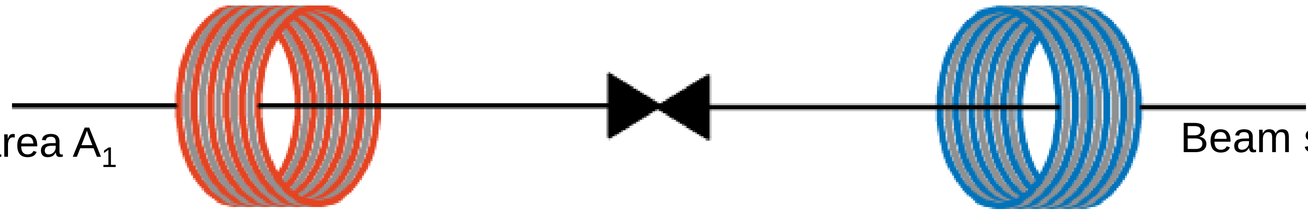
However,
LHC has a total stored beam energy
10^{14} protons x $14 \cdot 10^{12}$ eV ~ 10^8 J

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

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

from C. Joram, SSL 2003

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

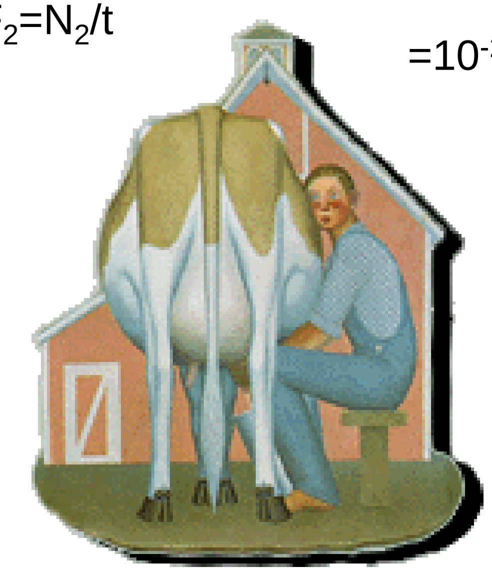


$=10^{-28}$ m^2

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

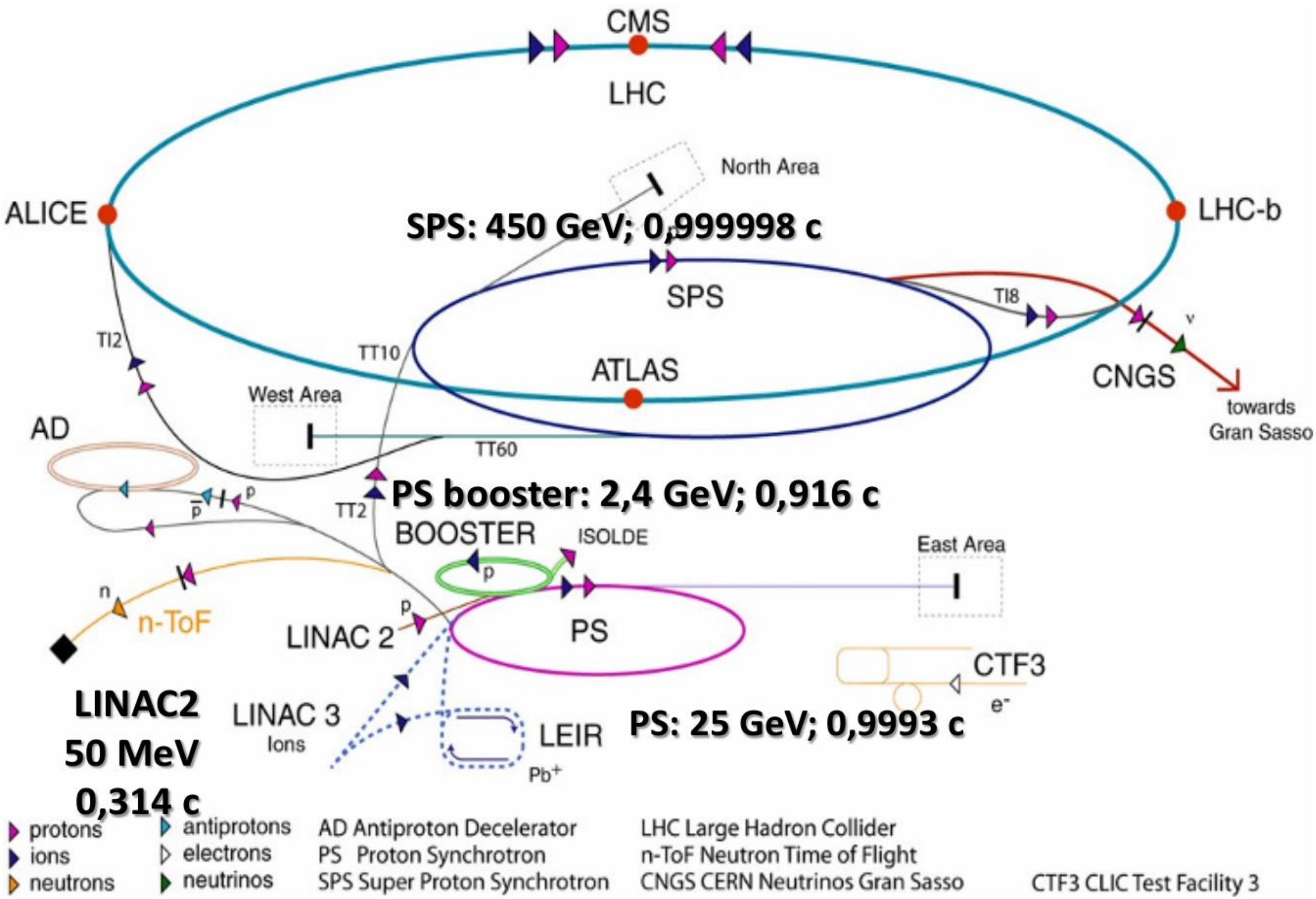
- At early LHC in 100 days of operation per year: $\int \mathcal{L} dt$ ~ 10 fb^{-1} for $\mathcal{L}$ ~ 10^{33} $cm^{-2}s^{-1}$
- Next e^+e^- machines ➔ few 10 x ab^{-1}

To reach unexplored area of HEP:

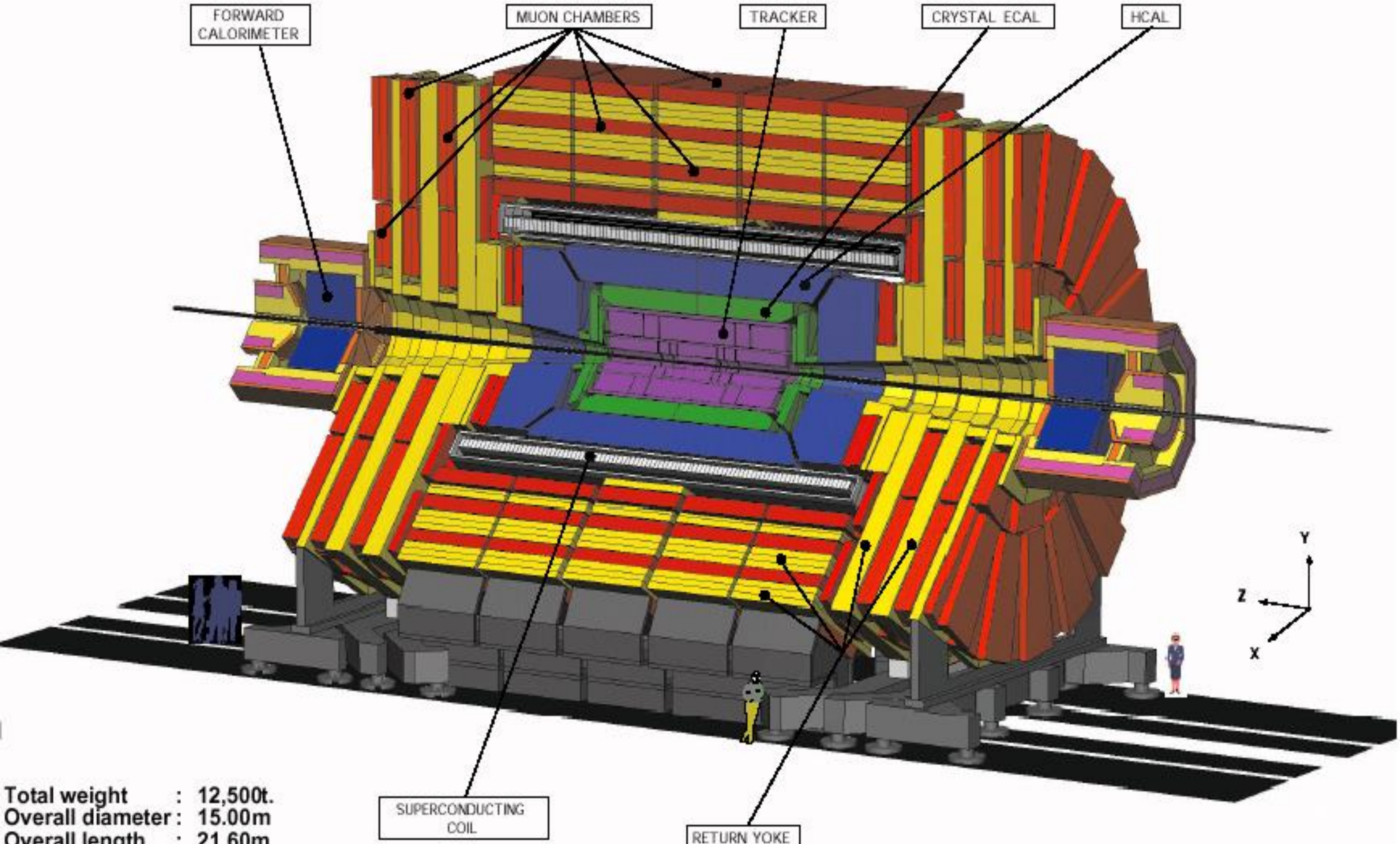
- ⇒ Increase Energy
- ⇒ Increase Luminosity
- ⇒ Increase Precision

Increase Energy, Increase Luminosity } Accelerators

Increase Precision { Theory & Analysis; **Detectors**

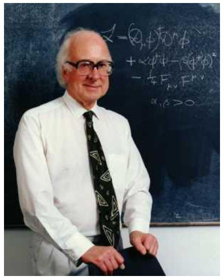

CMS
LHC
North Area
ALICE
LHC-b
SPS: 450 GeV; 0,999998 c
SPS
TI8
TI2
TT10
ATLAS
CNGS
towards
Gran Sasso
West Area
AD
TT60
PS booster: 2,4 GeV; 0,916 c
TT2
BOOSTER
ISOLDE
East Area
p
n
n-ToF
LINAC 2
PS
CTF3
e⁻
LINAC2
50 MeV
0,314 c
LINAC 3
Ions
LEIR
Pb⁺
PS: 25 GeV; 0,9993 c
protons
ions
neutrons
antiprotons
electrons
neutrinos
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso
CTF3 CLIC Test Facility 3

CMS
A Compact Solenoidal Detector for LHC



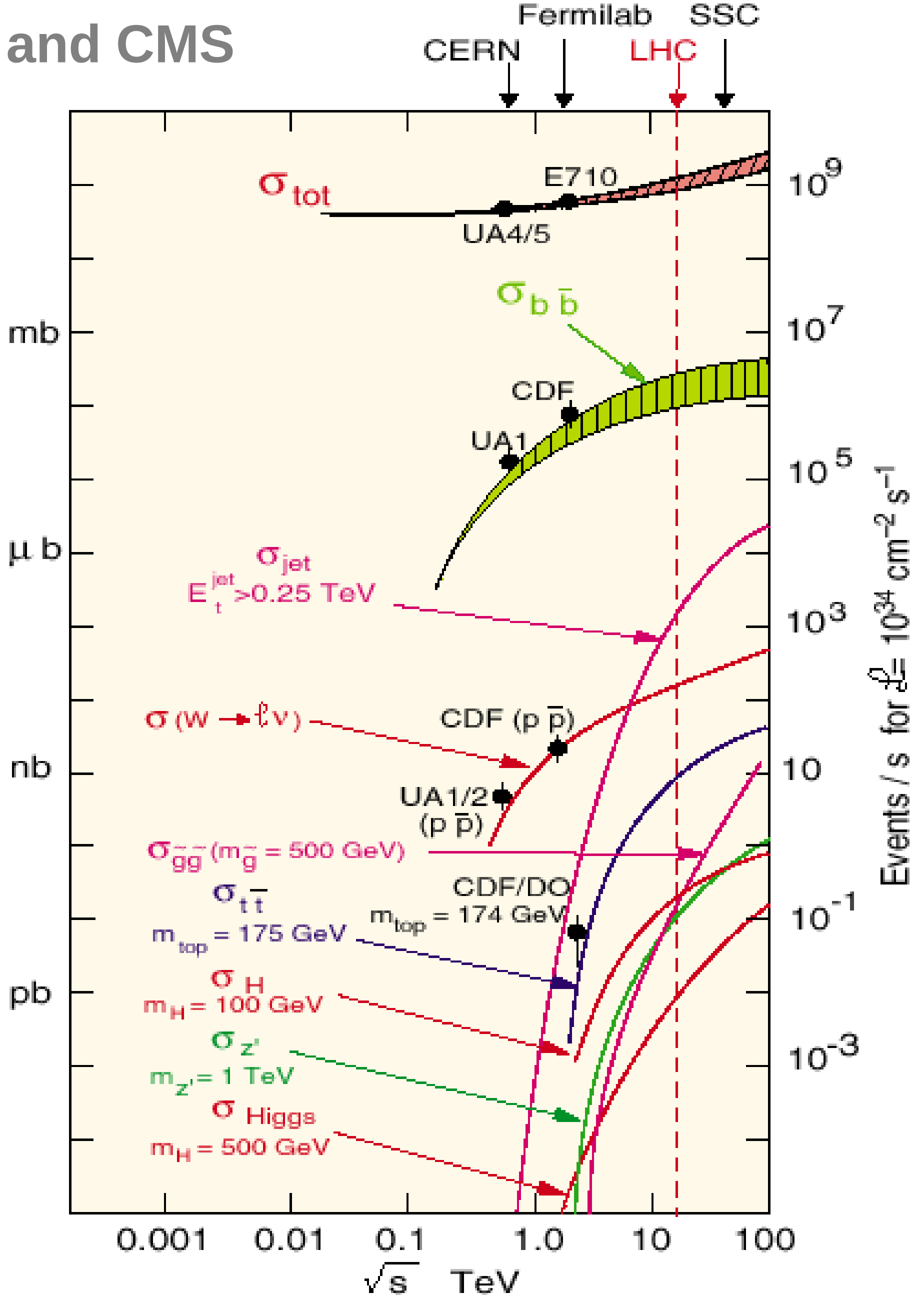
Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

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

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.

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

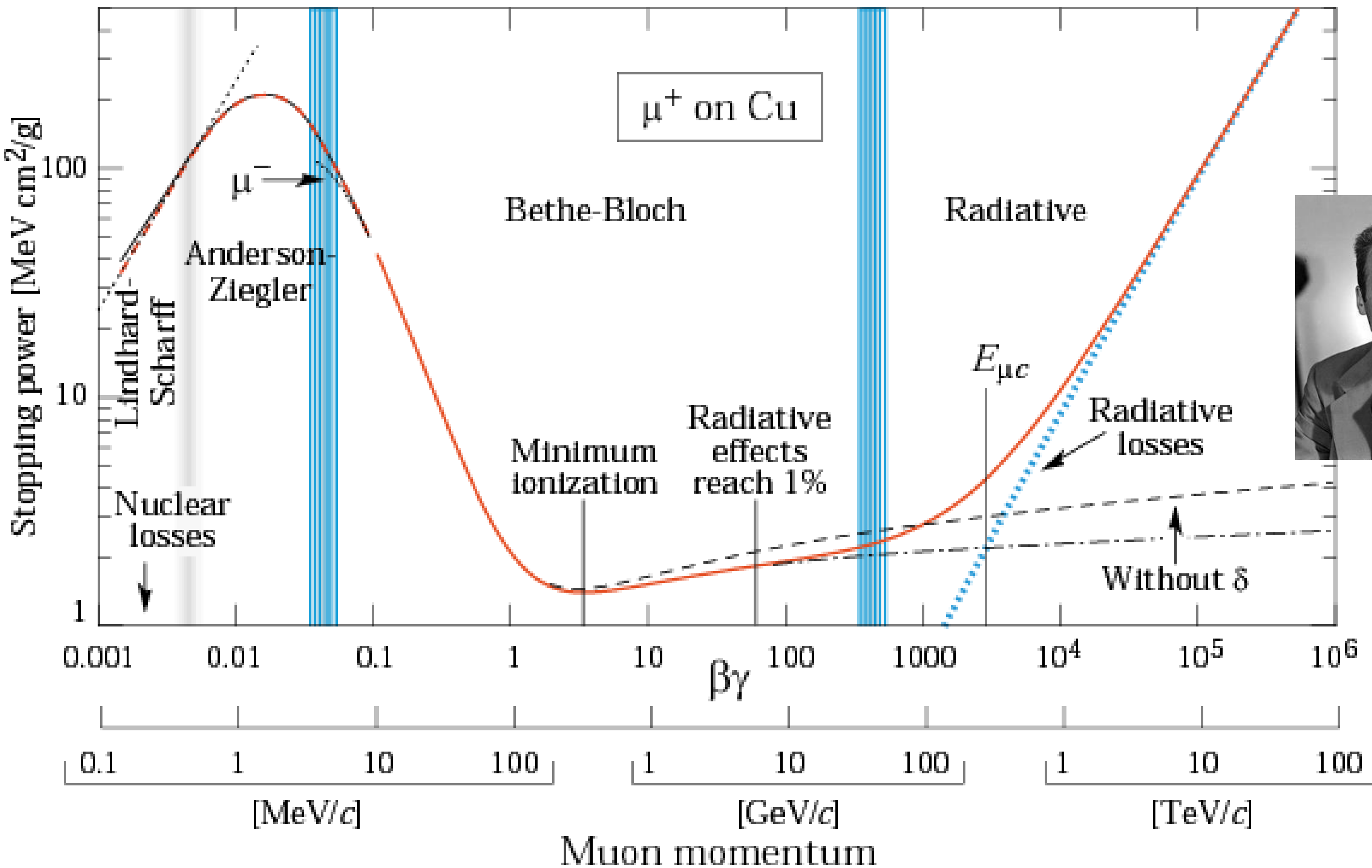
- Instead of ionization/excitation real photon can be produced under certain conditions

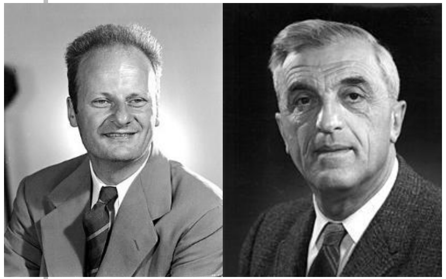
  ➔ Cherenkov or Transition radiation

  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 :

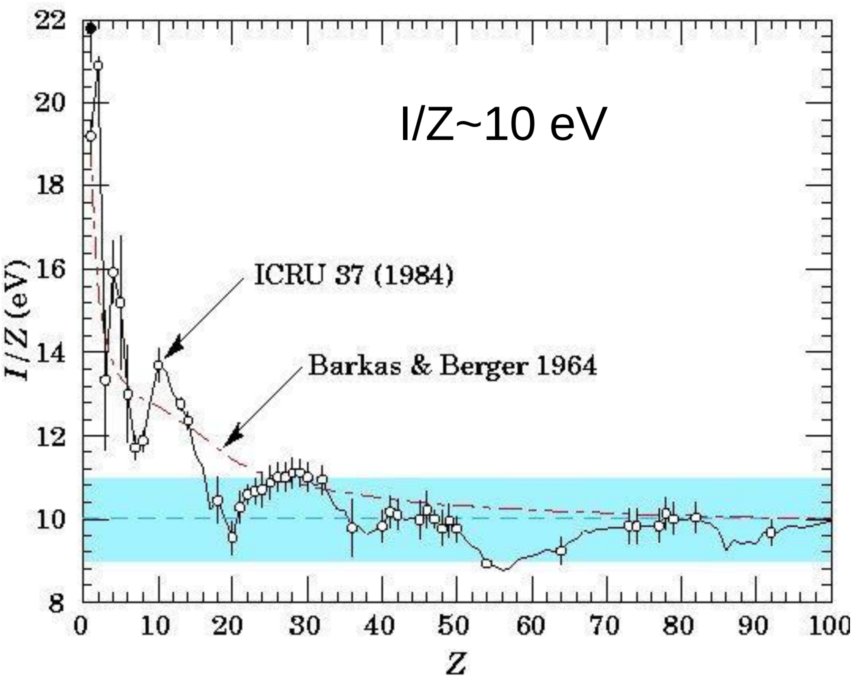
$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

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

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



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

Bethe-Bloch at Low energy :

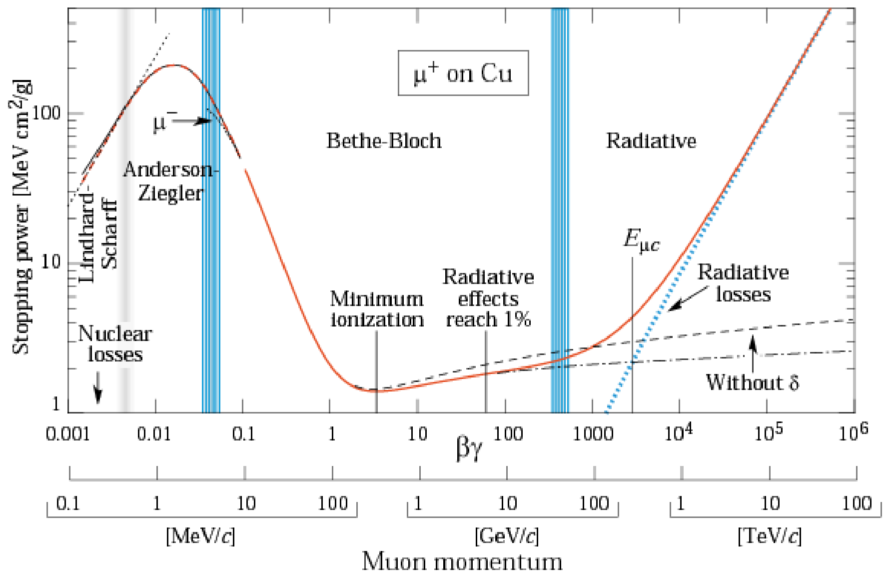
- C/Z : shell correction to account for atomic binding. At low energy the incident particles have less chance to interact with the electronic inner orbits. For copper ~1% at $\beta\gamma=0.3$

- $0.01 < \beta < 0.05$: 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

- 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:

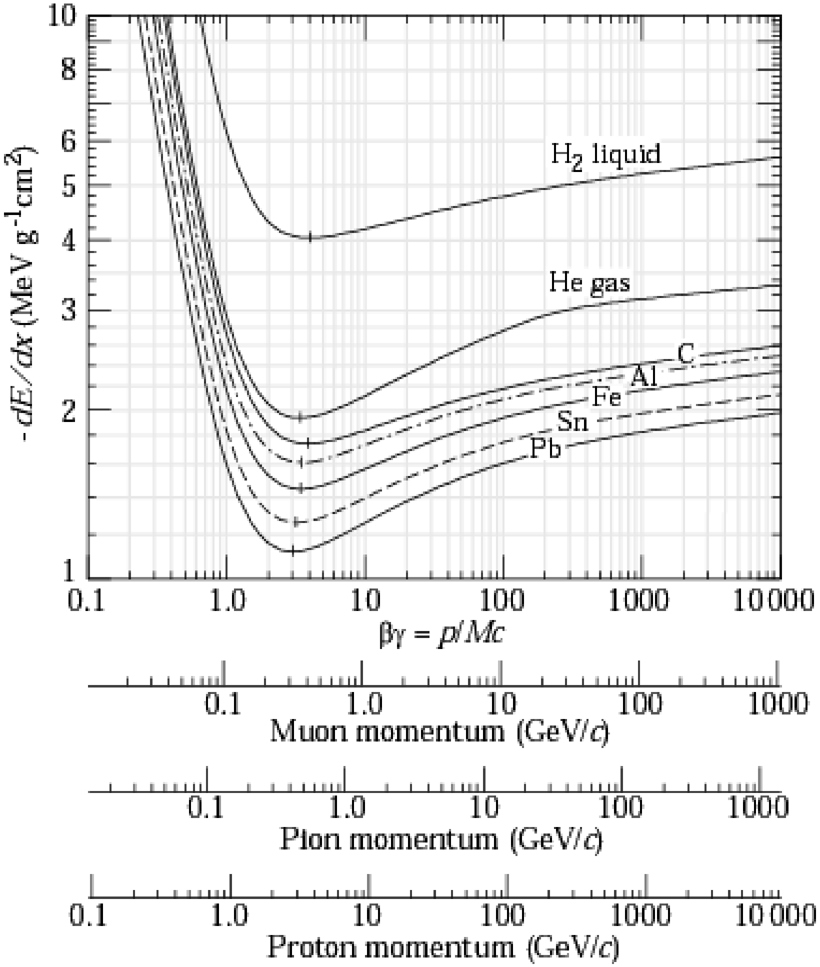
$\delta/2 \rightarrow \ln(\hbar\omega_p/I)+\ln\beta\gamma-1/2$

Bethe-Bloch at High energy: density effect

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

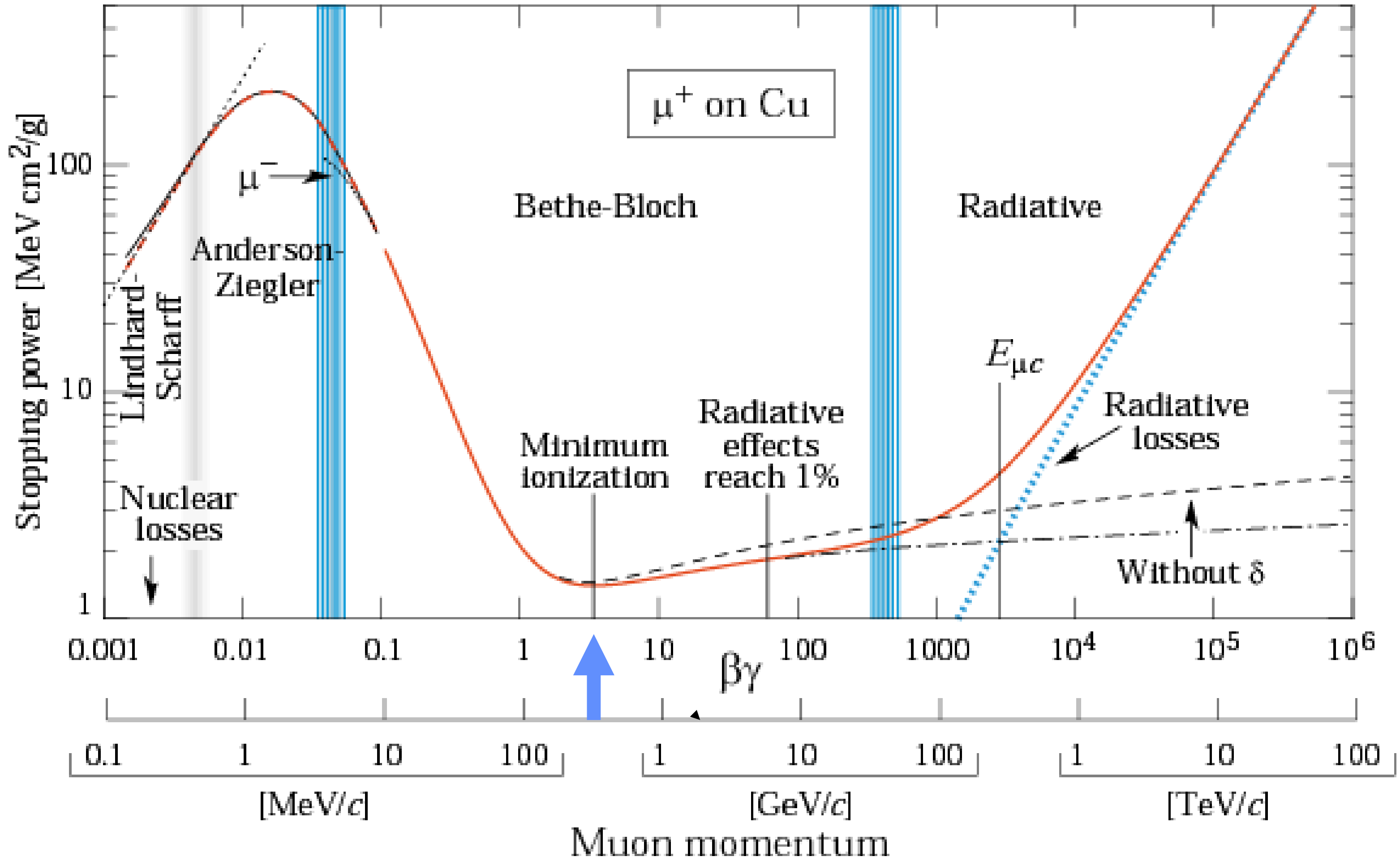
Remaining relativistic rise from the $\beta^2\gamma$ growth of T_{max}, due to (rare) large energy transfers to a few electrons

When these events are excluded
➔ Fermi plateau



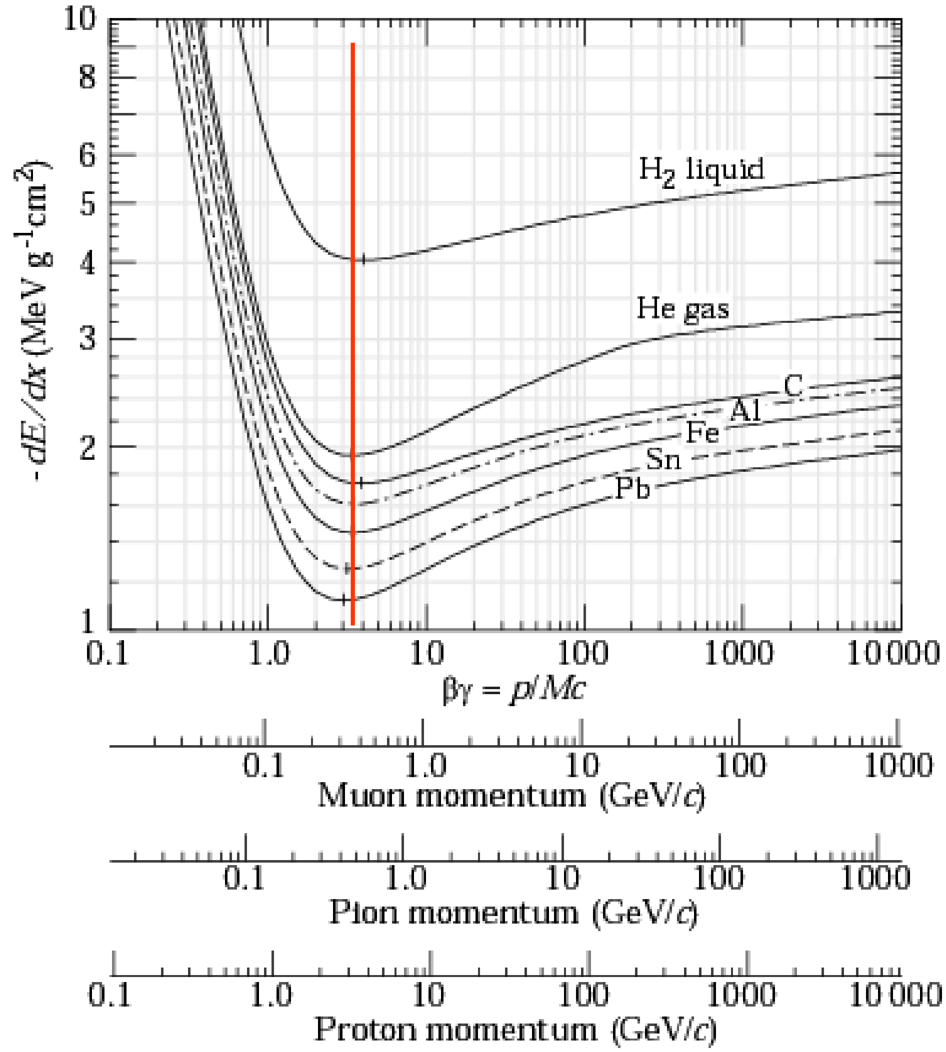
Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminium, iron, tin, and lead.

Minimum Ionizing Particle :



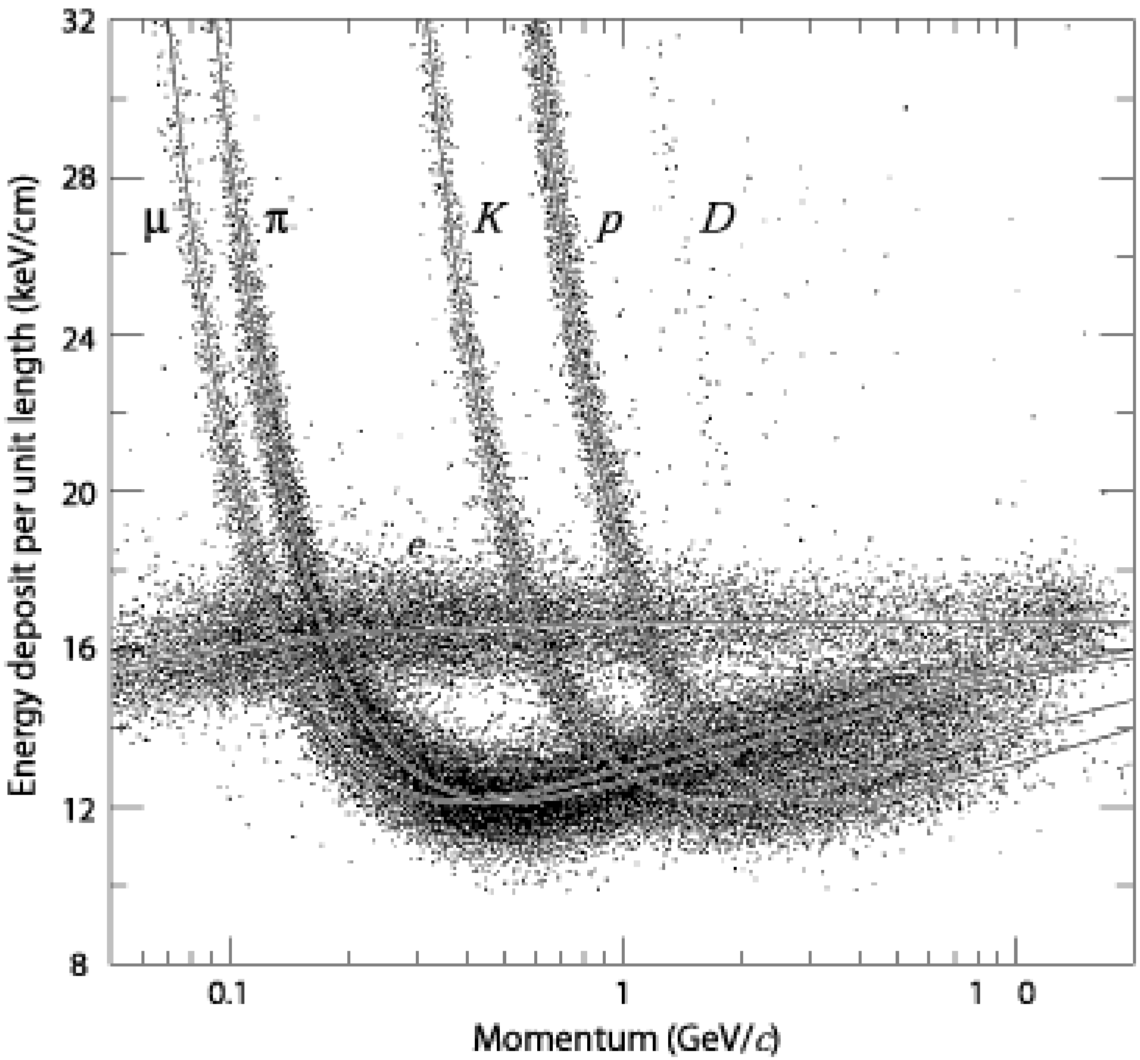
The minimum is approximately independent of the material

- Minimum at 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

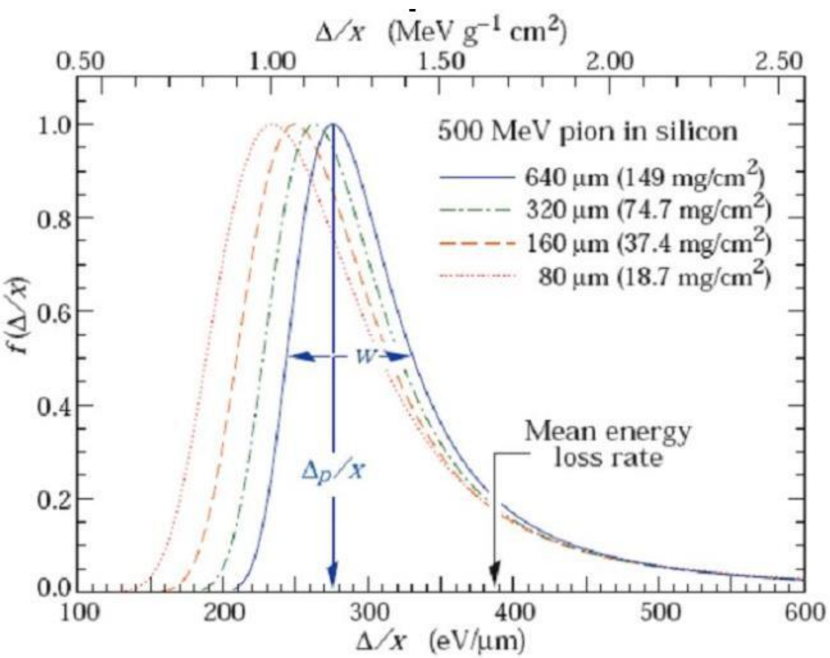
Particle ID relying on d*E*/d*x* depends on p (and δp) and particle_hypothesis_1,2

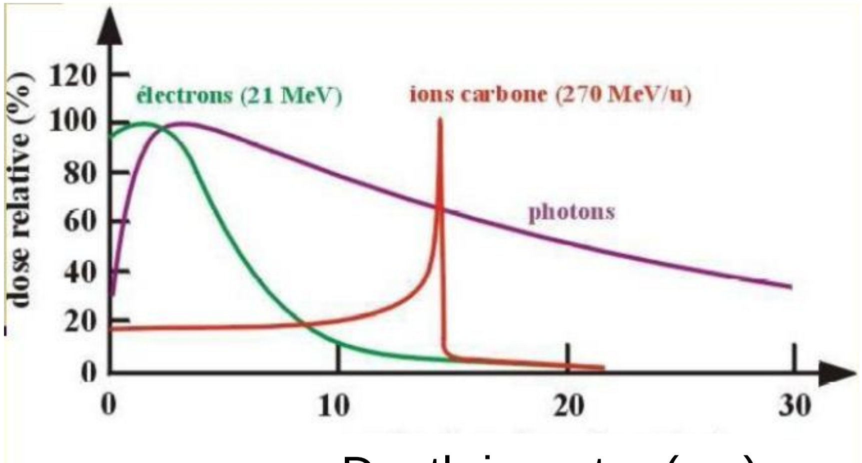
Bethe Bloch describes the average energy loss. For moderate thickness absorber fluctuations on this energy loss described by a Landau distribution.
For thin absorber (small dx) fluctuations become large

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)

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

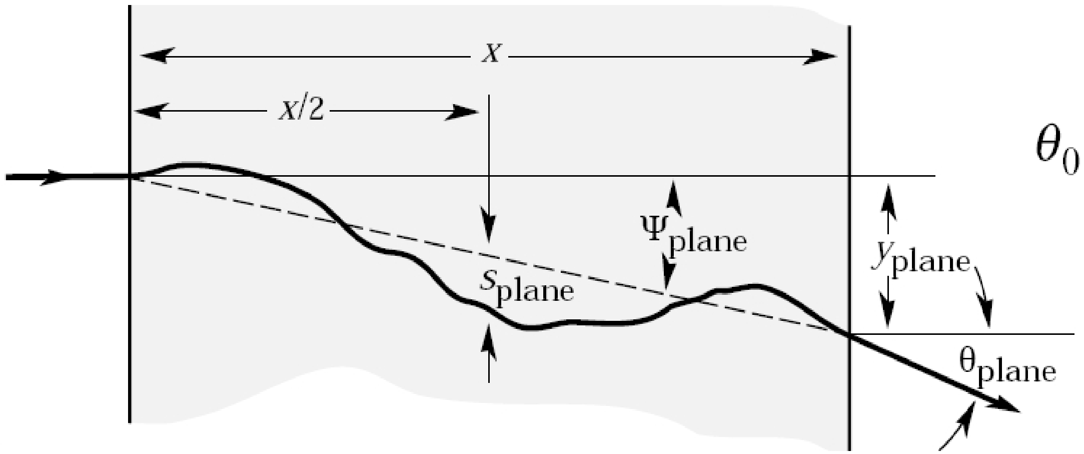
Muons can be considered as a MIP with 2 MeV/(g/cm^2)
→ 2 MeV in 1 cm scintillator
→ 2 keV in 1 cm of gas
To stop a 450 GeV muon beam, will need 900 m of concrete (density 2.5) !

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

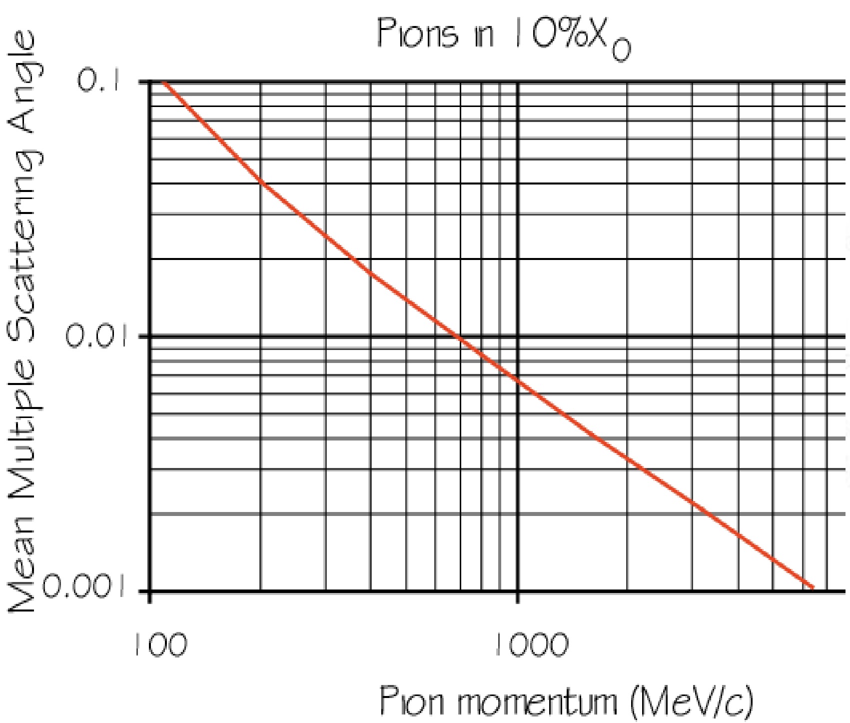
- A charged particle traversing a medium is deflected by many small-angle scatters mainly due to Coulomb scattering from nuclei → multiple scattering. Affects precision of tracking performance

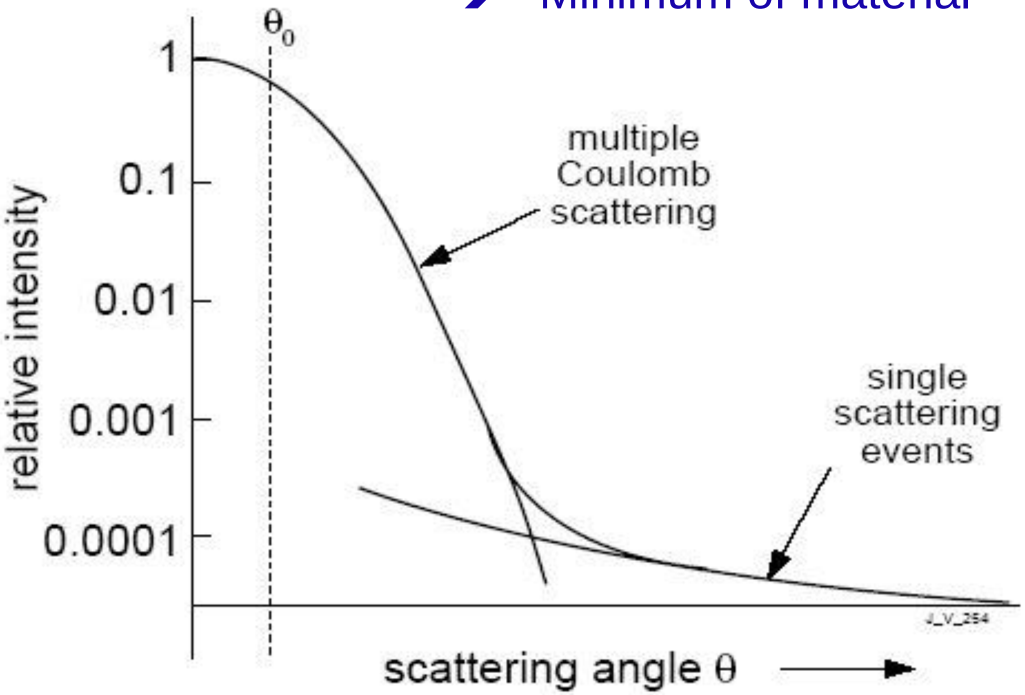


$$\theta_0 = \frac{13.6\,MeV}{\beta c p} z \sqrt{\frac{L}{X_0}} \left\{ 1 + 0.038 \ln\left(\frac{L}{X_0}\right) \right\}$$

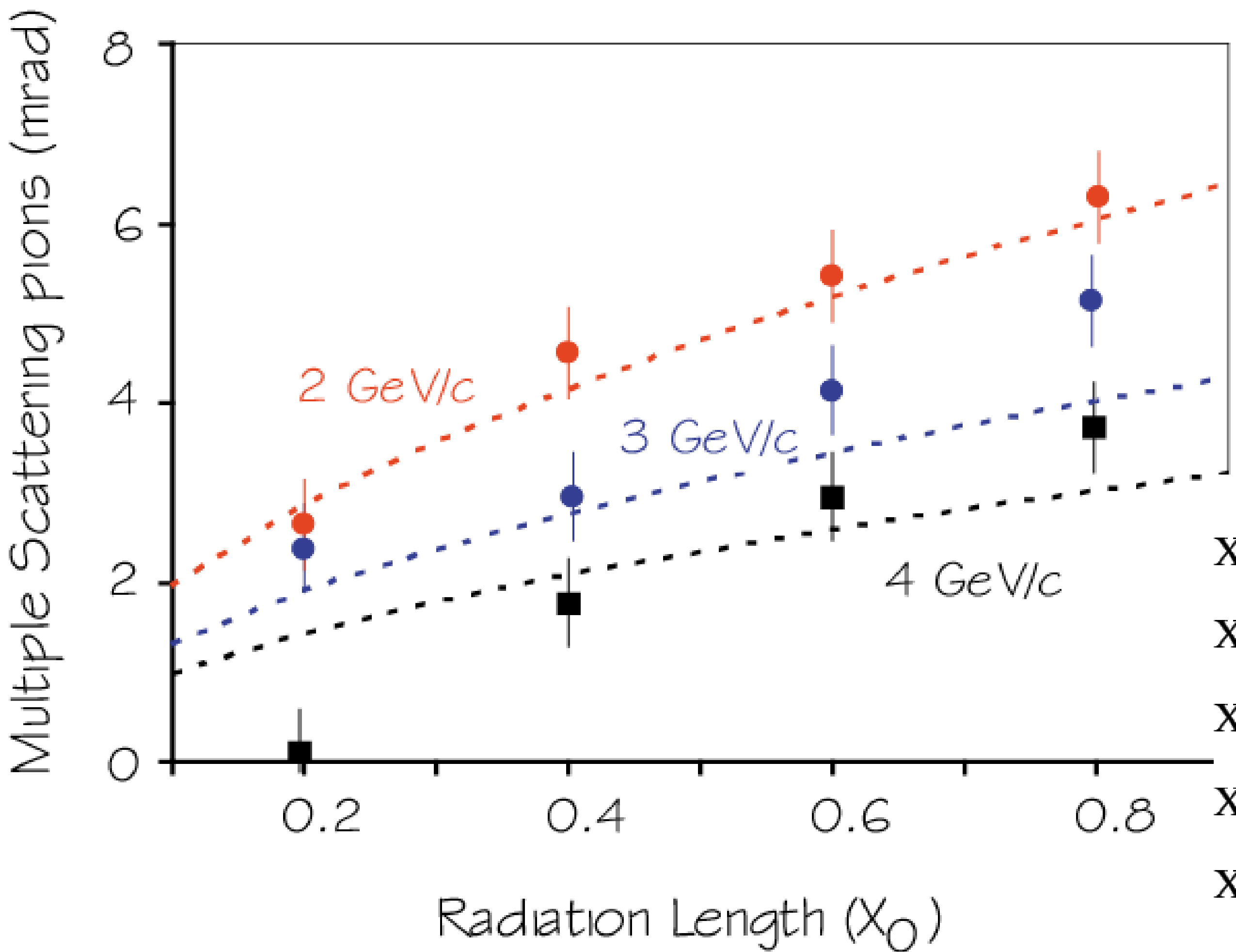
Smaller for high energy,
for small material depth as measured in units of radiation length

→ Minimum of material



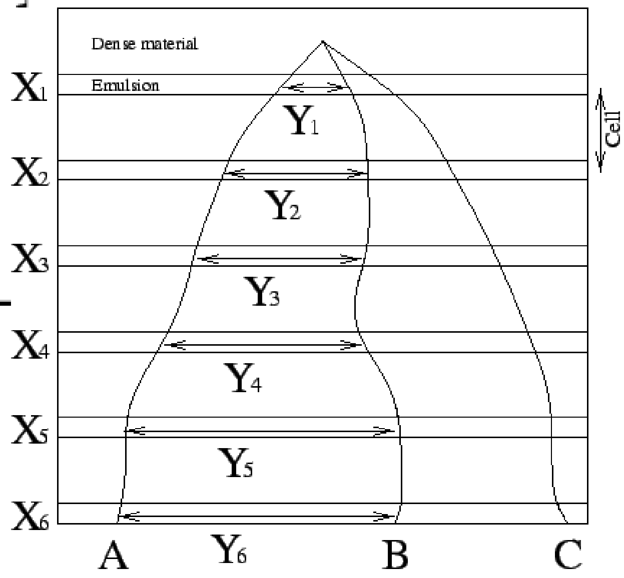


Effect of "0" if averaged for many particles, and seen as a fluctuation on a given one



OPERA

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



… 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

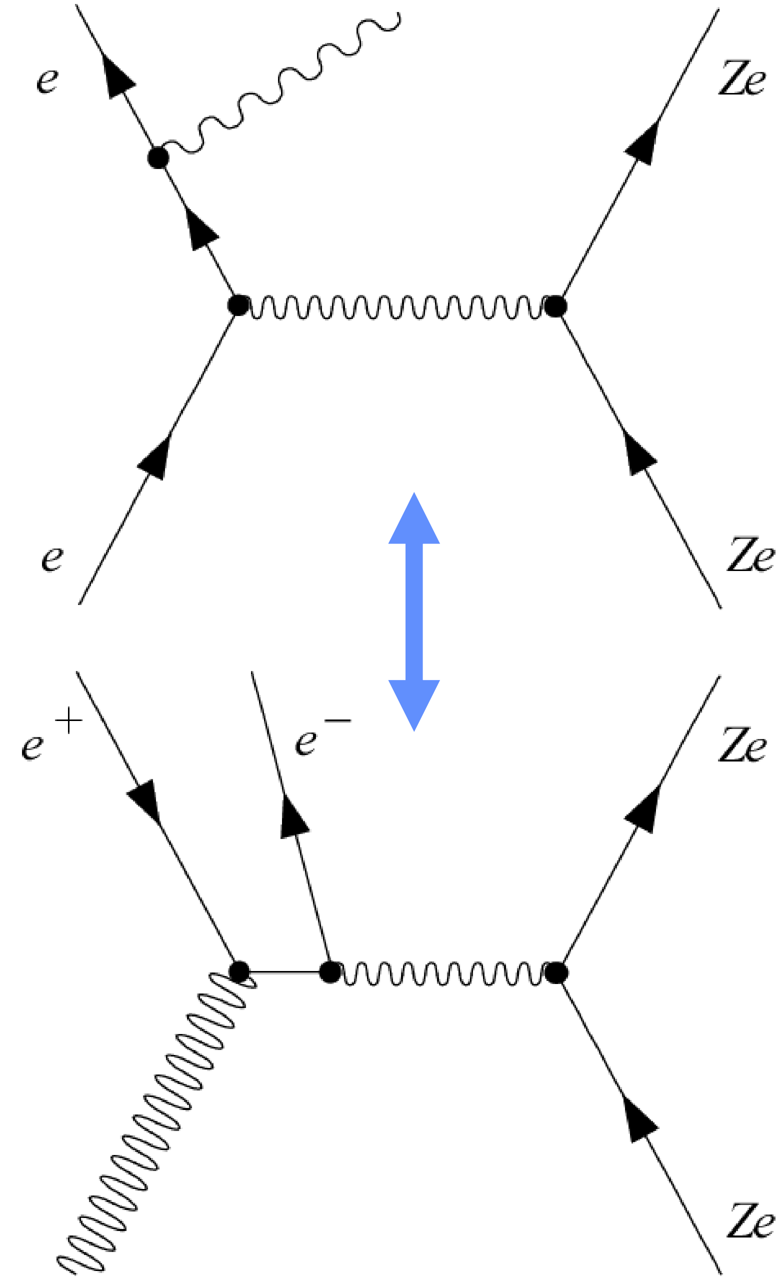
- ❑ Bremsstrahlung: emission of photon by scattering with the nucleus electrical field

  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.

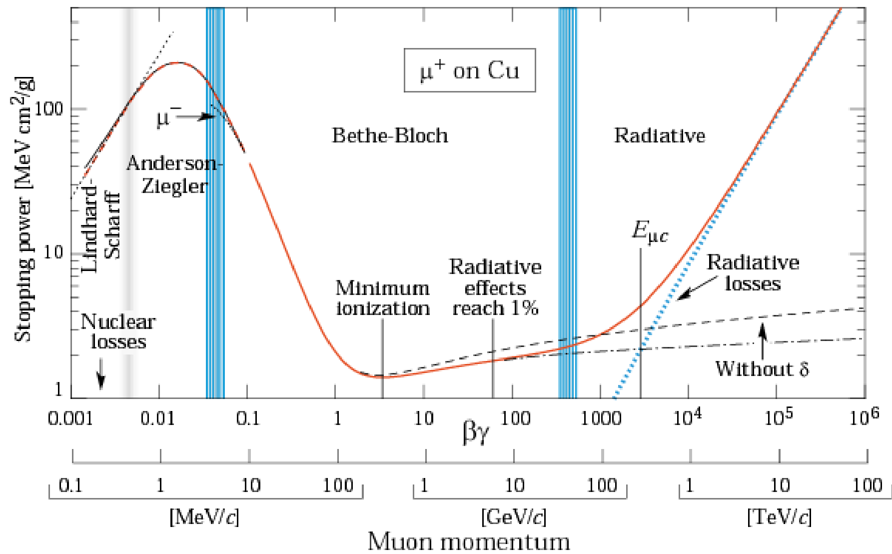
➔ *we now have an additional photon*



Pair production

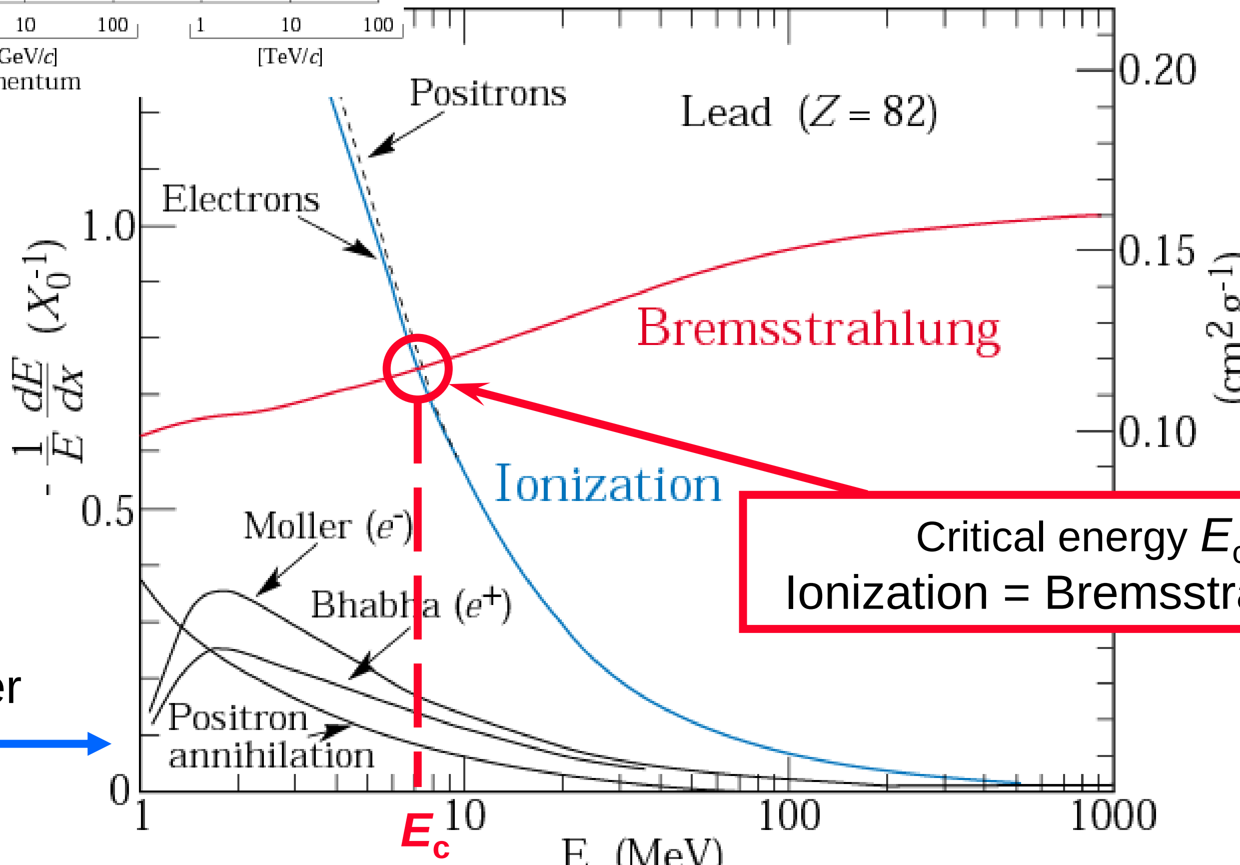
Creation of an electron/positron pair in the field of an atom.

➔ *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

1.7 19.6 196 **βγ**

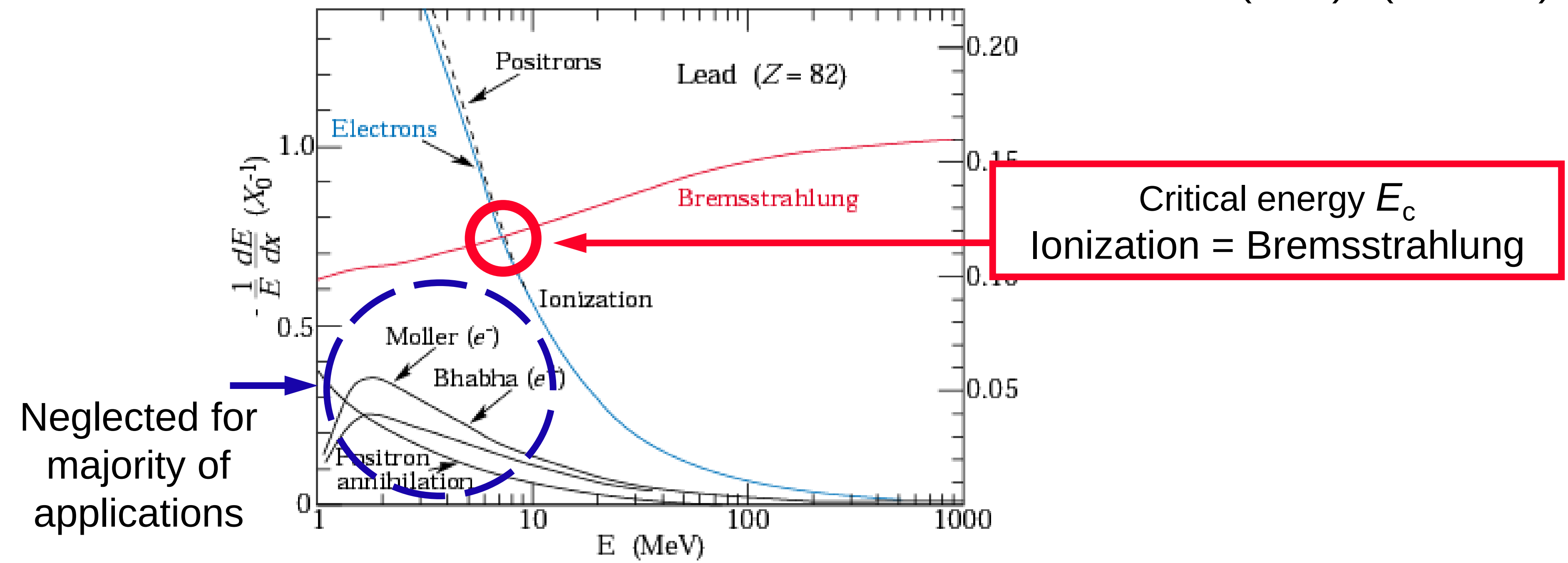
Define Radiation Length $\boldsymbol{X_o}$ as the Radiative Mean Path :

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

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:

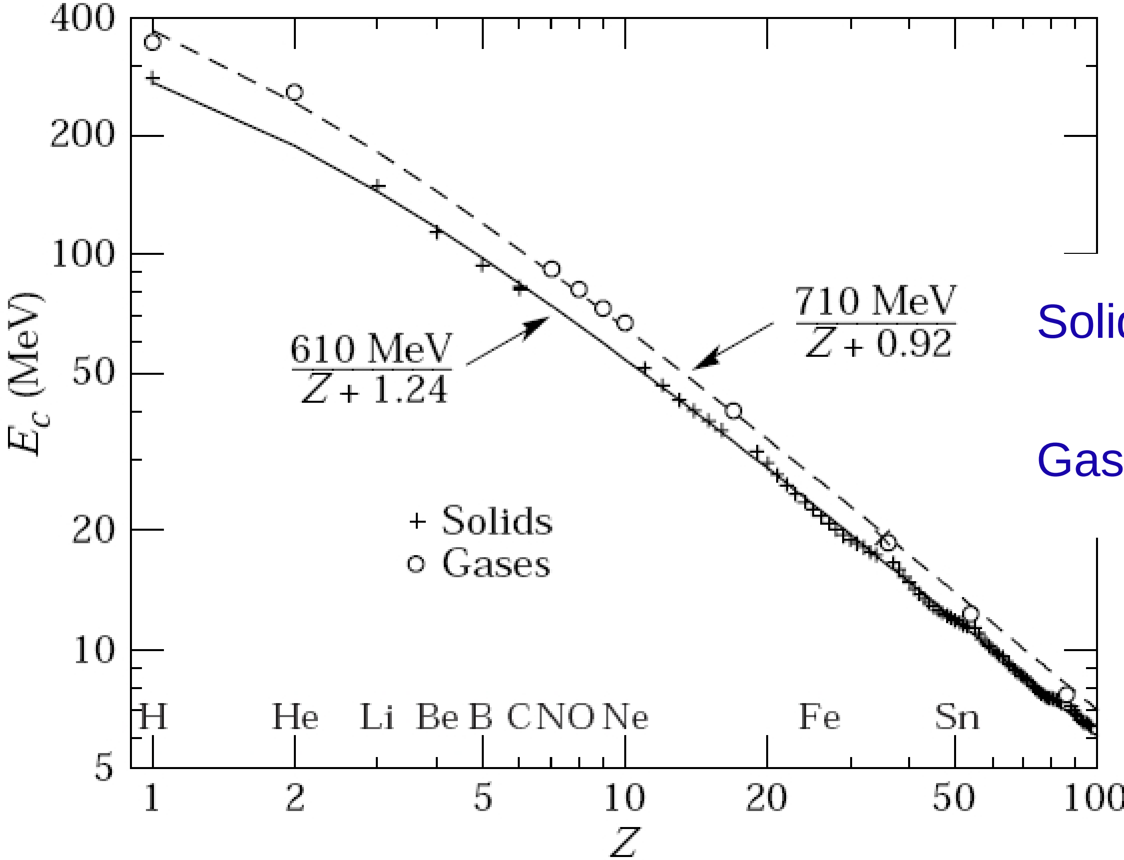
$$X_0 = \frac{716.4\,\mathrm{g.cm^{-2}}\,A}{Z(Z+1)\ln(187/\sqrt{Z})}$$



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

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

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 → three major physics mechanisms :

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

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

Strong dependence with Z, dominant at low photon energy

- Compton scattering

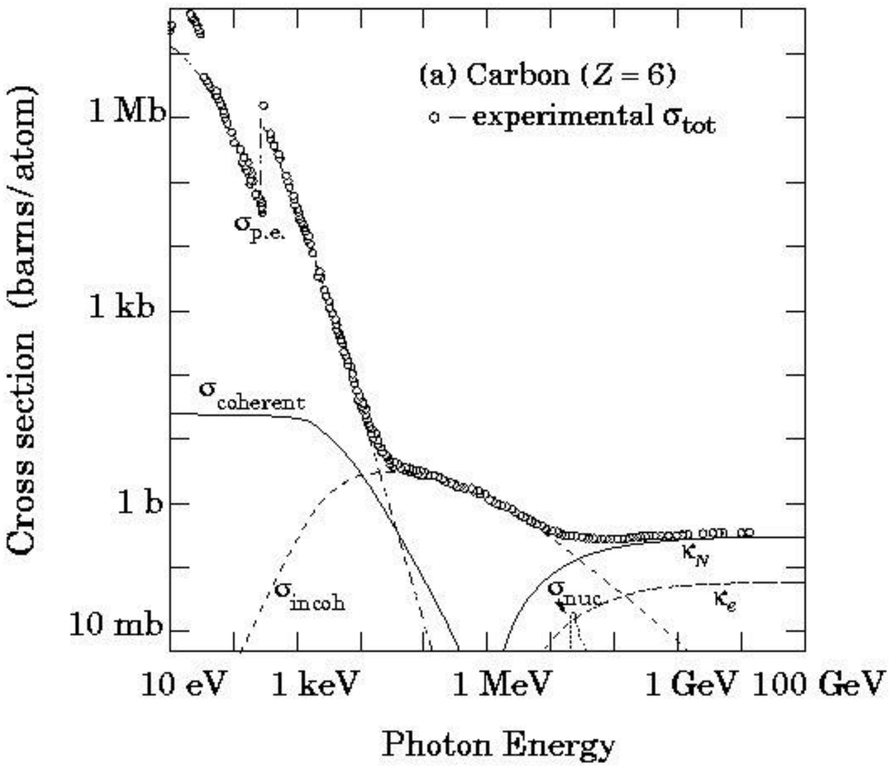
$$\sigma_C^e \propto \frac{\ln E_\gamma}{E_\gamma} \text{ and atomic compton} = Z\,\sigma_C^e$$

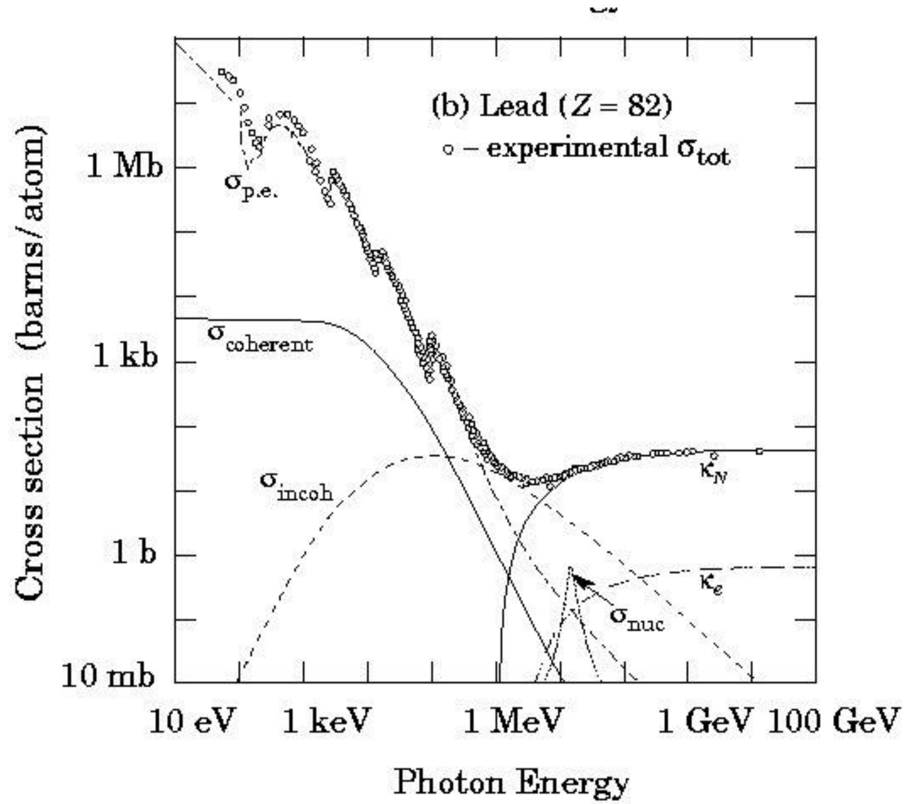
- Pair creation (similar to Bremsstrahlung) : dominant for $E \gg m_e c^2$

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

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





$\sigma_{\text{p.e.}}$ = 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

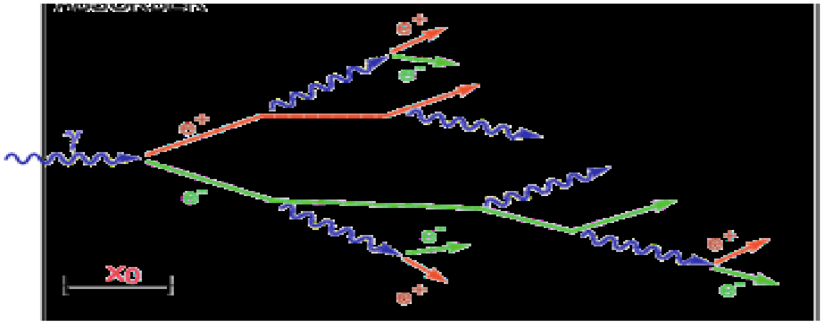
6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

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`.

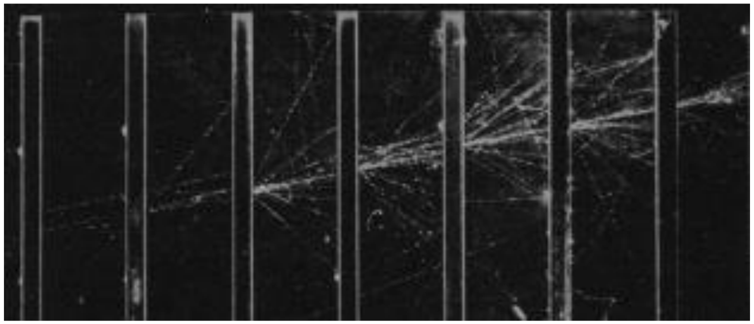
Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T $\{g/cm^2\}$	Nuclear [a] interaction length λ_I $\{g/cm^2\}$	$dE/dx\|_{min}$ [b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length [c] X_0 $\{g/cm^2\}$	X_0 $\{cm\}$	Density $\{g/cm^3\}$ ($\{g/\ell\}$ for gas)	Liquid boiling point 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		—

Electromagnetic showers

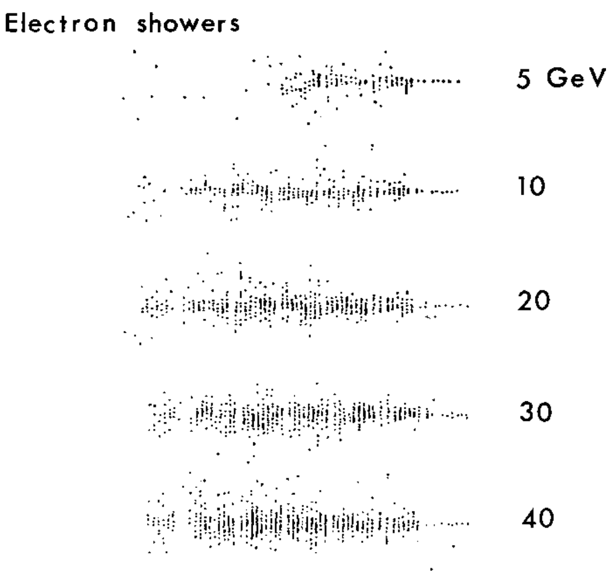
A high energy electron or photon incident on a thick absorber, initiates an EM cascade as pair production and Bremsstrahlung generate more electrons and photons with lower energy.

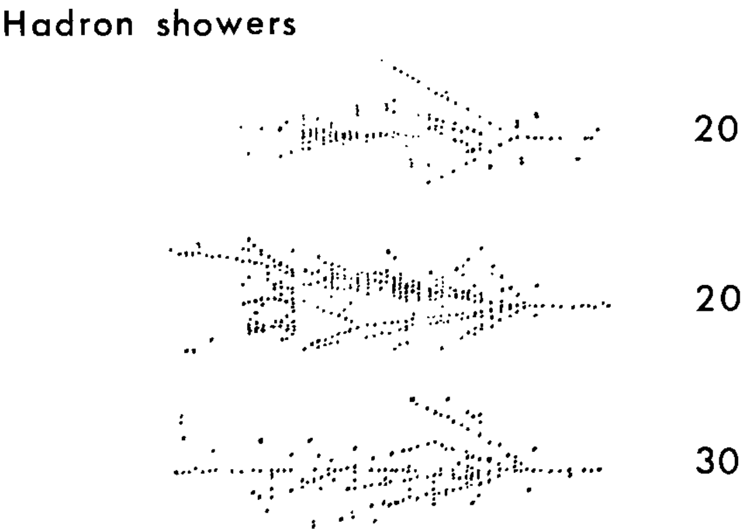


EM shower development



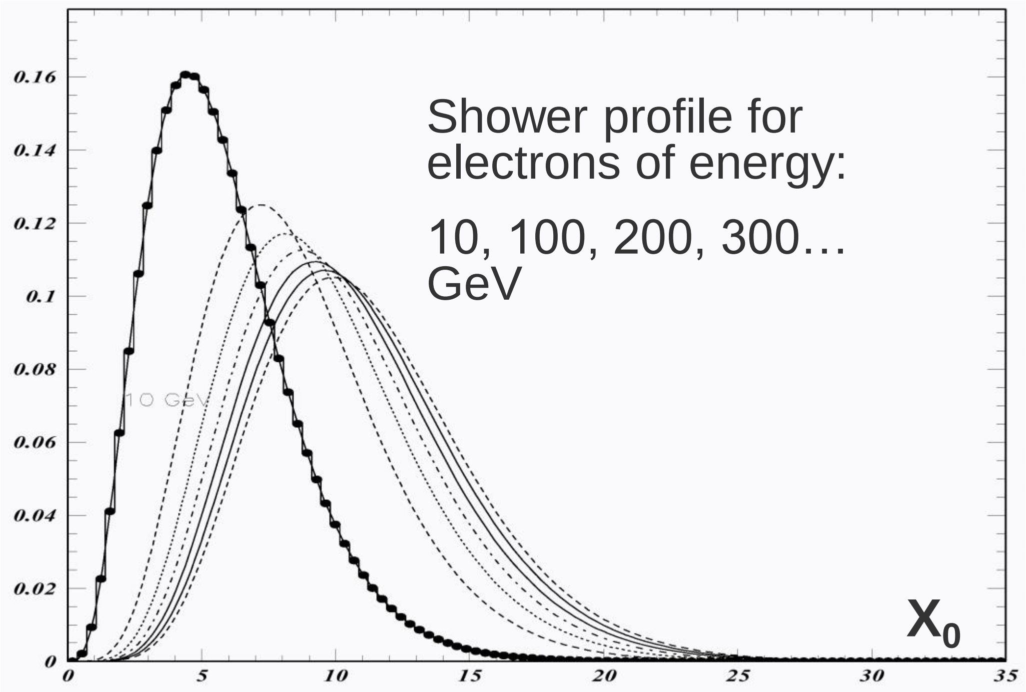
Lead absorbers in cloud chamber





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

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 $1X_0$

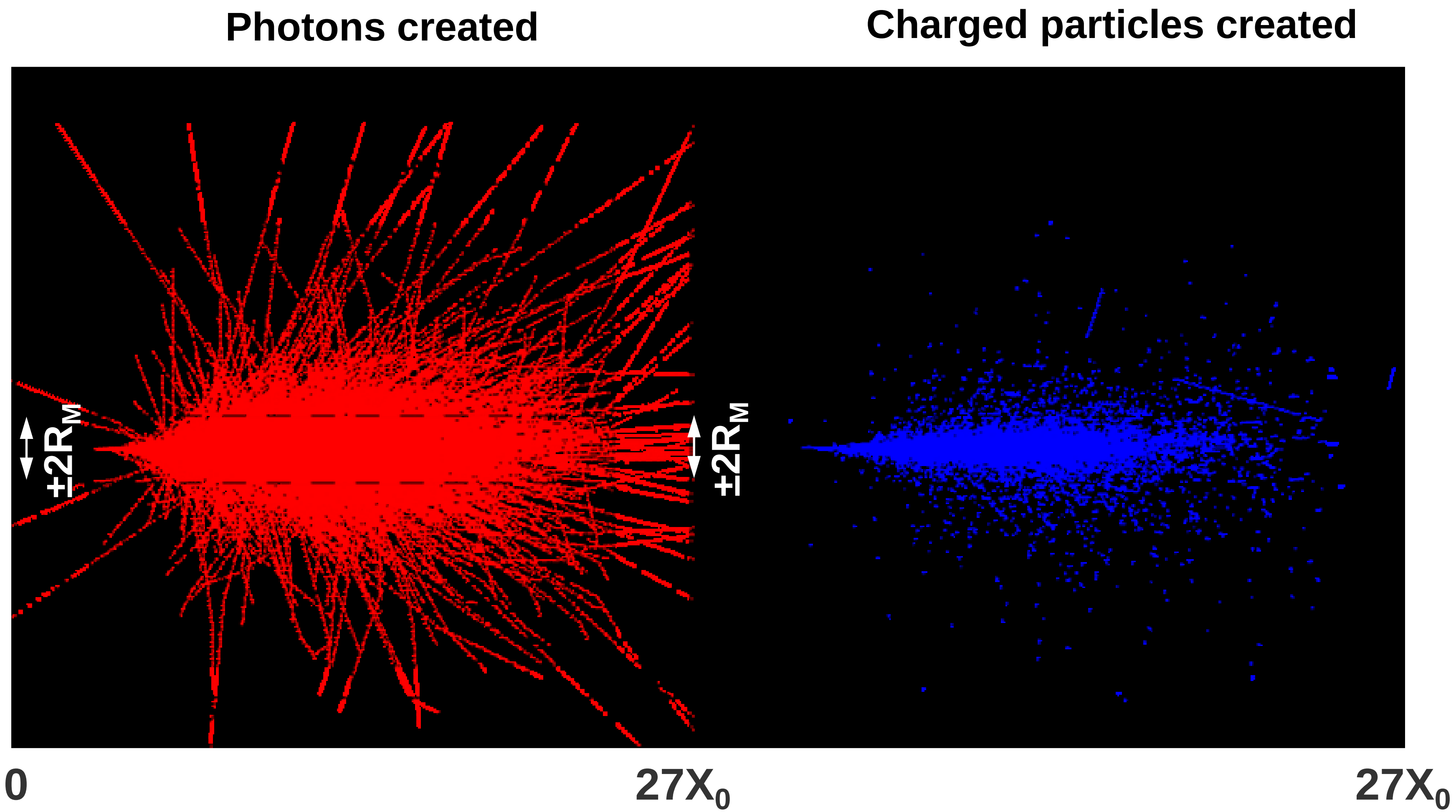
$$R_M = \frac{21\text{MeV}}{E_C} X_0 \quad (Z >> 1)$$

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)

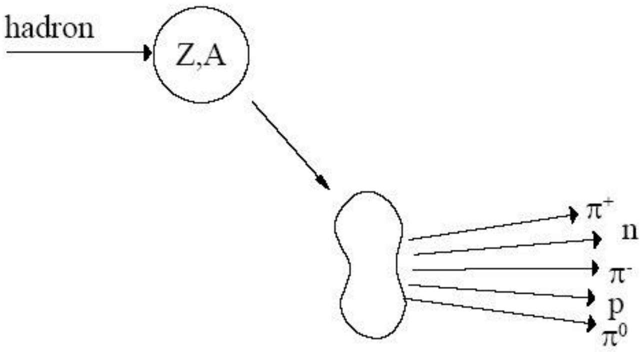


GEANT simulation: 100 GeV electron shower in the NA48 liquid Krypton calorimeter

From D. Cockerill

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

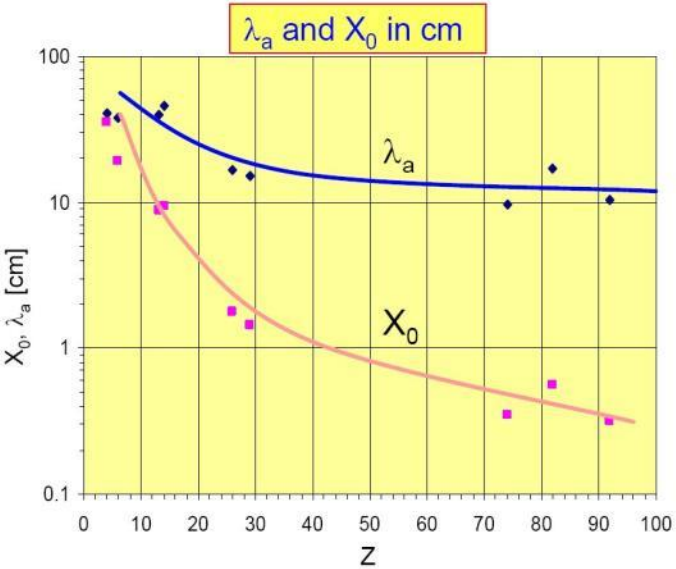
excitation and nucleus break up => production of secondary particles + fragment



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

For E > 1 GeV, $\sigma \sim \sigma_0 A^{0.7}$, 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 $\{g/cm^2\}$	$dE/dx\|_{min}$ [b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length [c] X_0 $\{g/cm^2\}$	X_0 $\{cm\}$	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		—

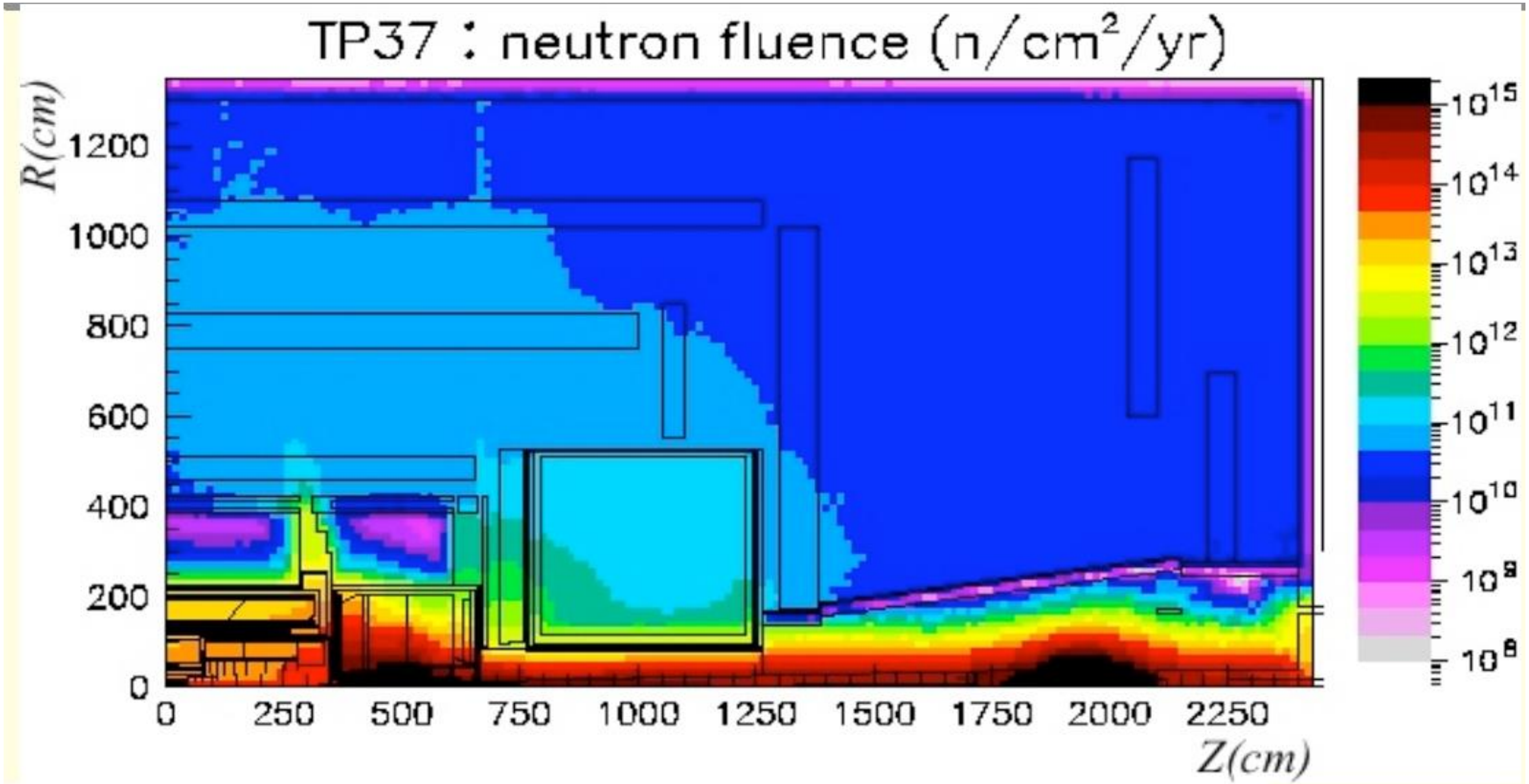
Neutron has no charge, can be detected only through charged particle produced in (weak or) strong interaction => short range => very penetrating

- 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 …

L. Serin



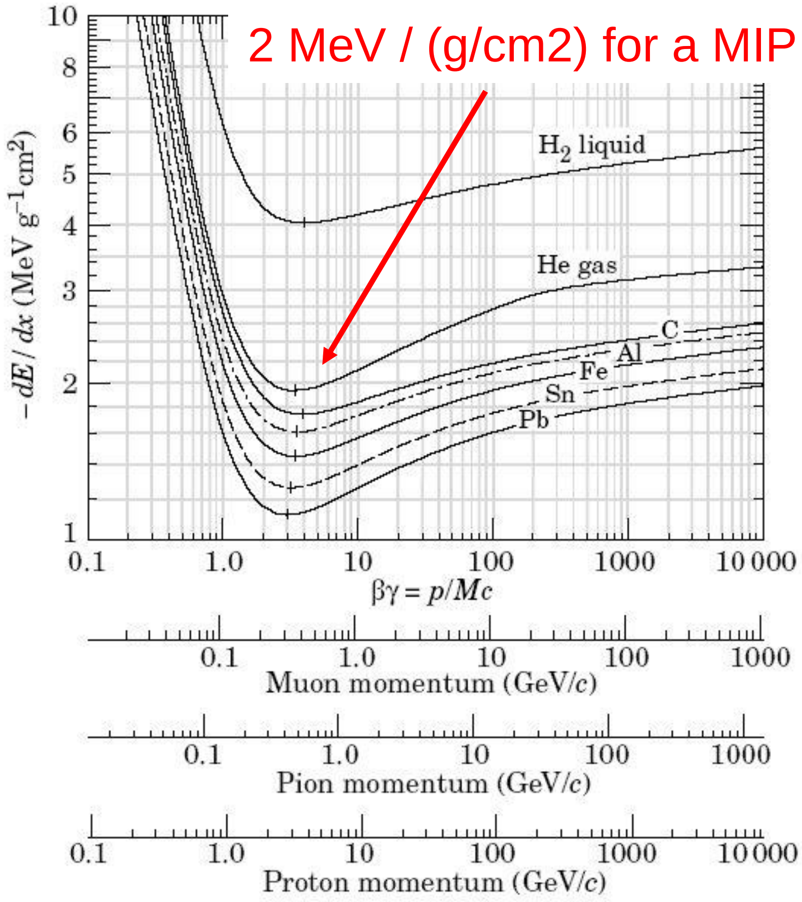
At r=11 cm, photons flux of 30 MRad !

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

- 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

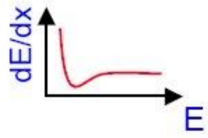
Bethe-Bloch for heavy charged particles



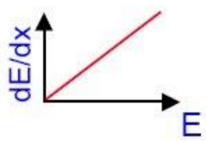
Radiation length X_0

e^+ / e^-

- Ionisation

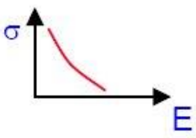


- Bremsstrahlung

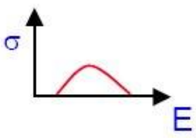


γ

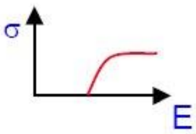
- Photoelectric effect



- Compton effect



- Pair production



Interaction of hadrons : many different particles produced, interaction length λ_I

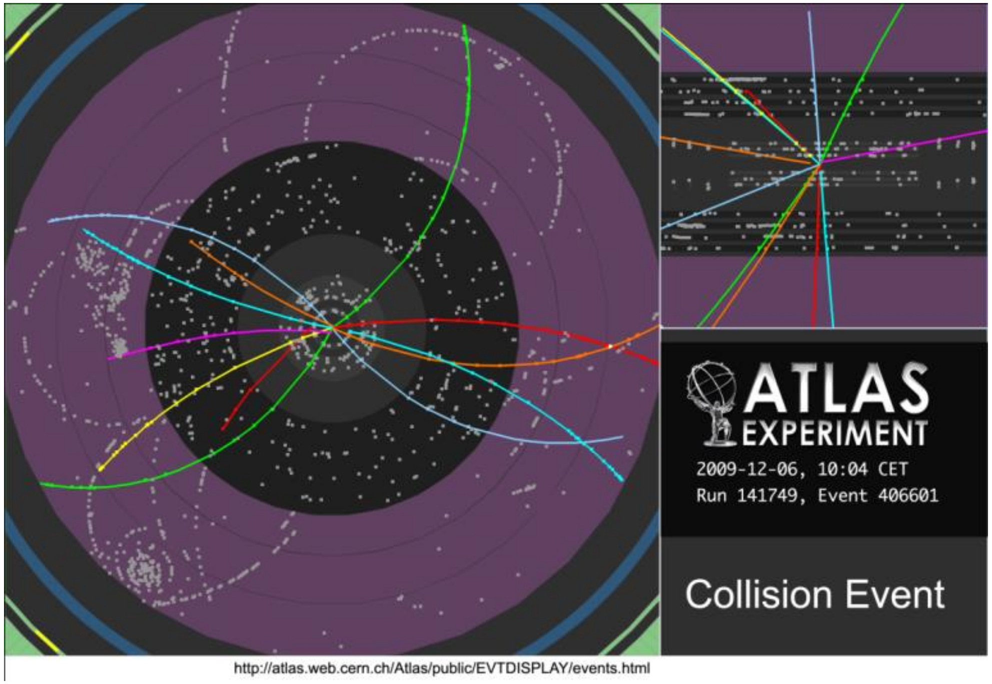
Now we are (almost) ready to built our first detector …

… but let us first look through common methods and tools

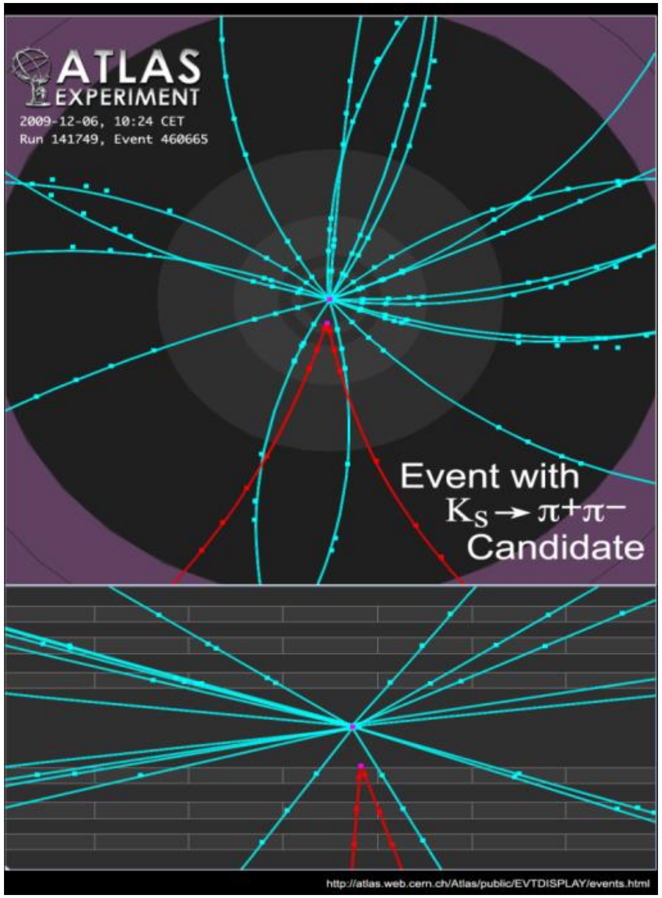
Gaseous detectors

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

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



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



Silicon detectors

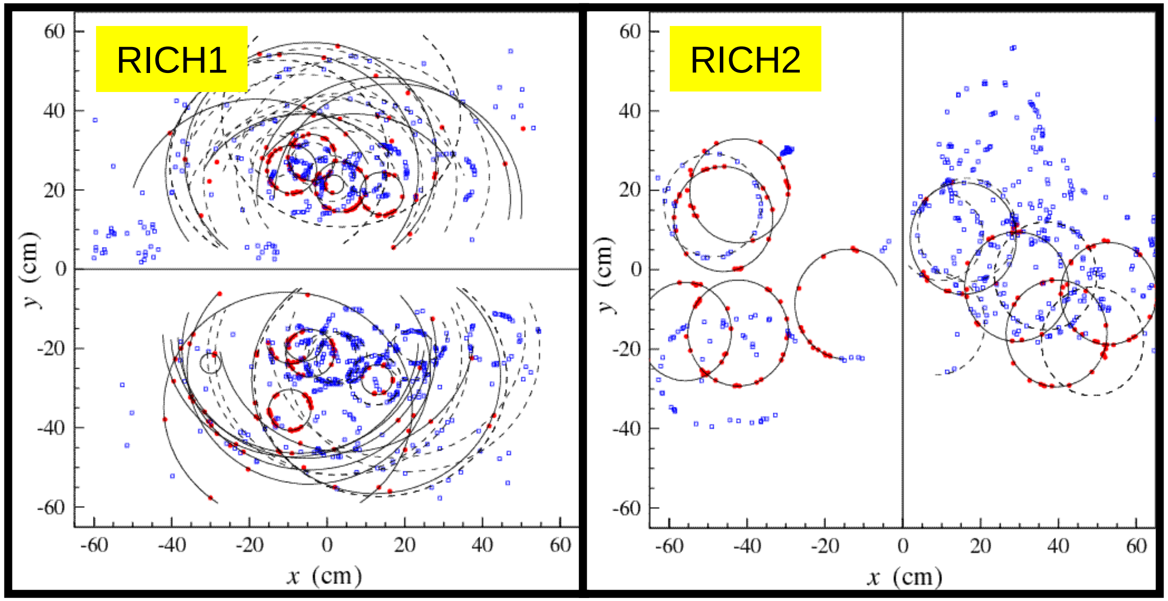
Measure: hits and/or amplitude
➔ Position resolution: ~ 5 μm
➔ Tracks & **Vertices** reconstruction

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
+ …

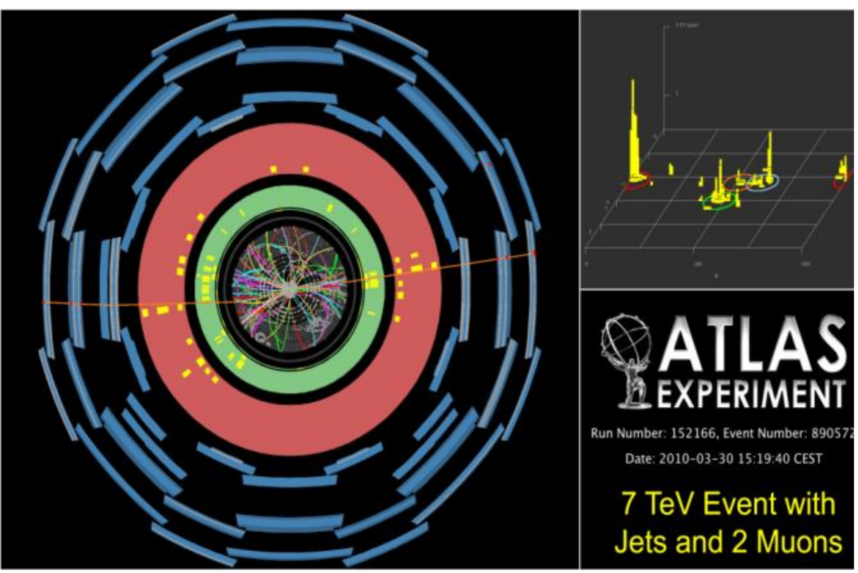
Calorimeters: electromagnetic and hadronic

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

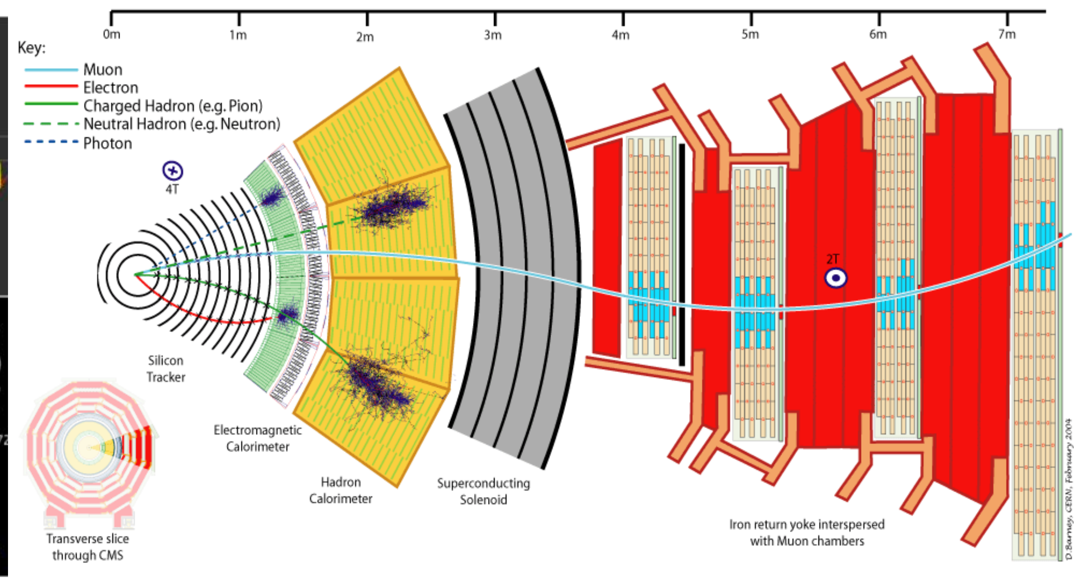
Muon detectors

Measure: Muon track after absorber
➔ Particle ID

Muons in ATLAS

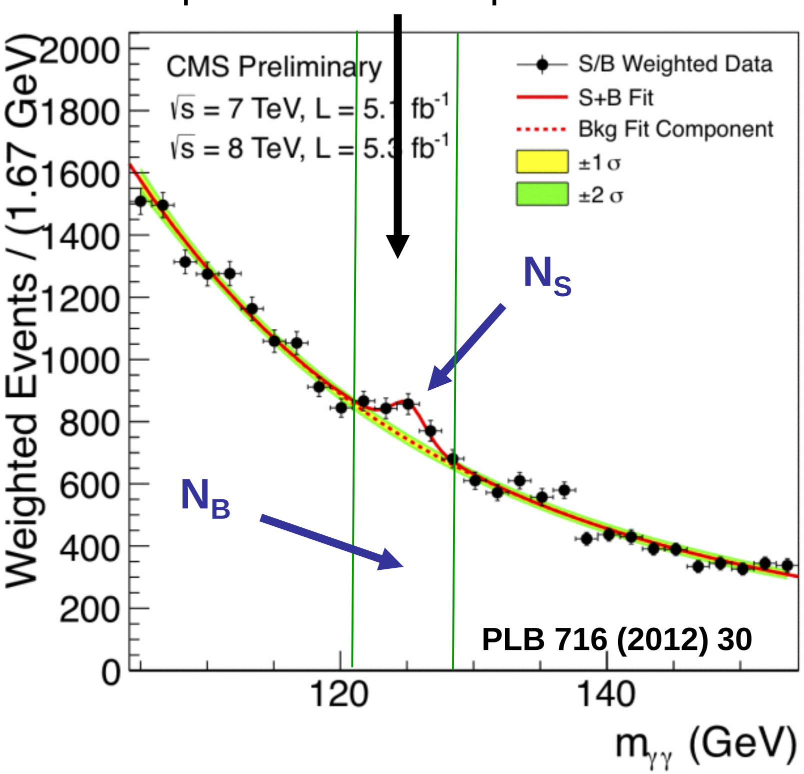


Muon in CMS



- **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

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

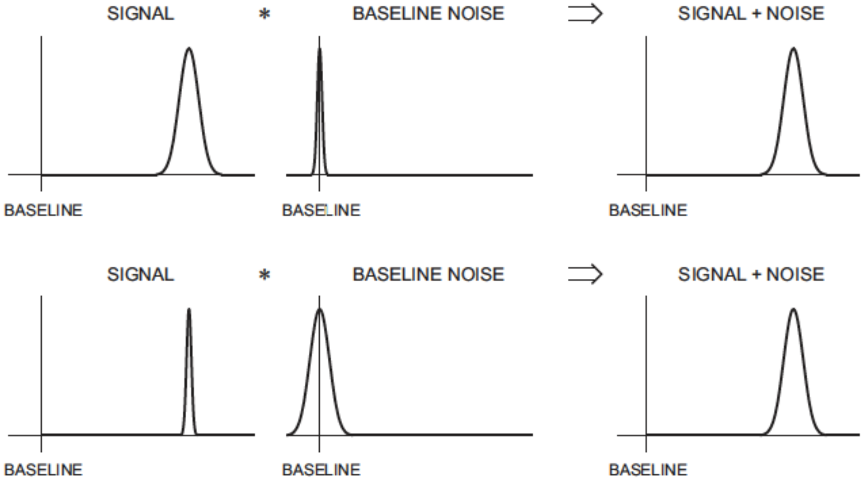
→ Enlarge data sample

→ Increase detector efficiency

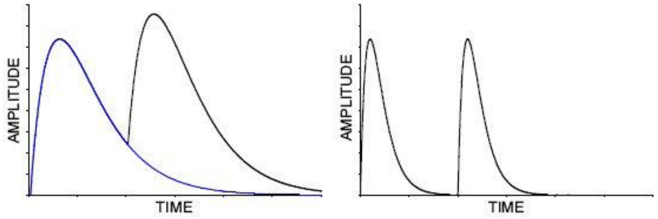
→ Reduce detector resolution

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

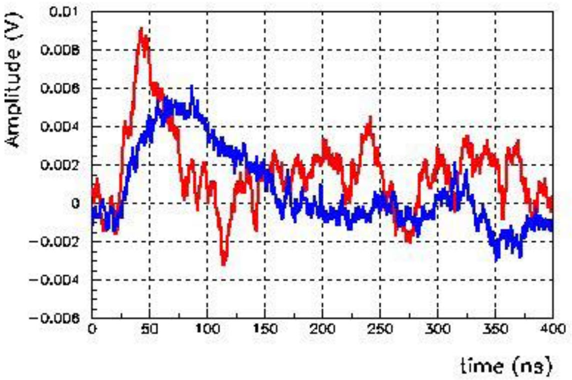
  - Every signal comes with its noise



  - Reduce pile-up

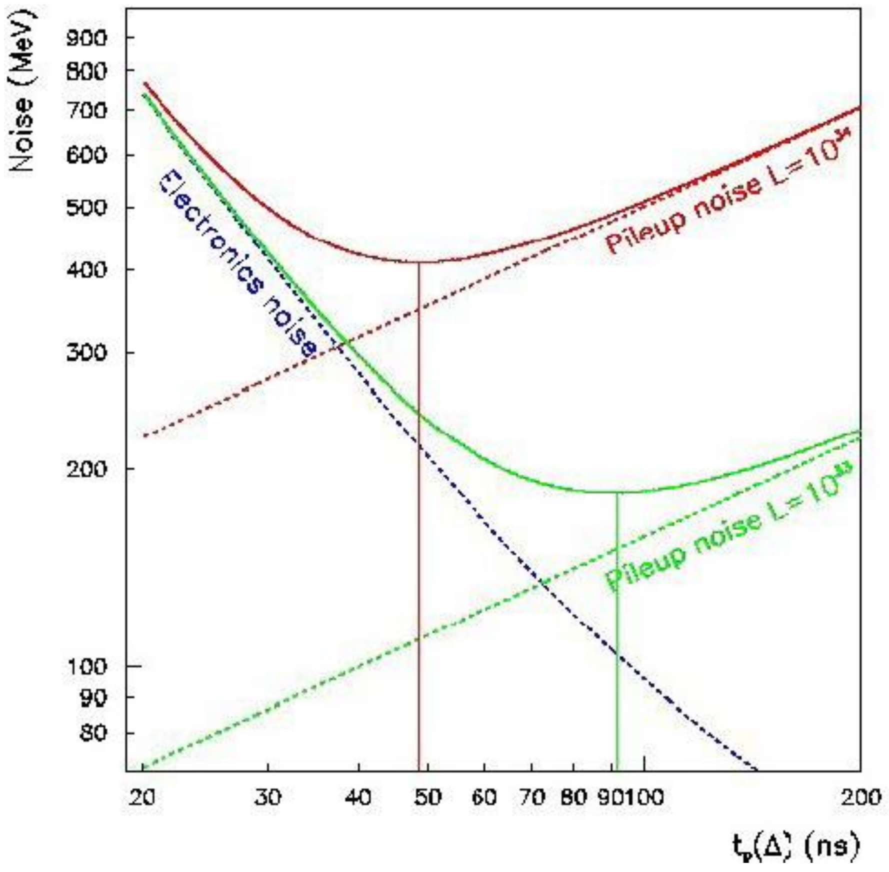


  - Realistic signal + noise shape



After E. Garutti et al.

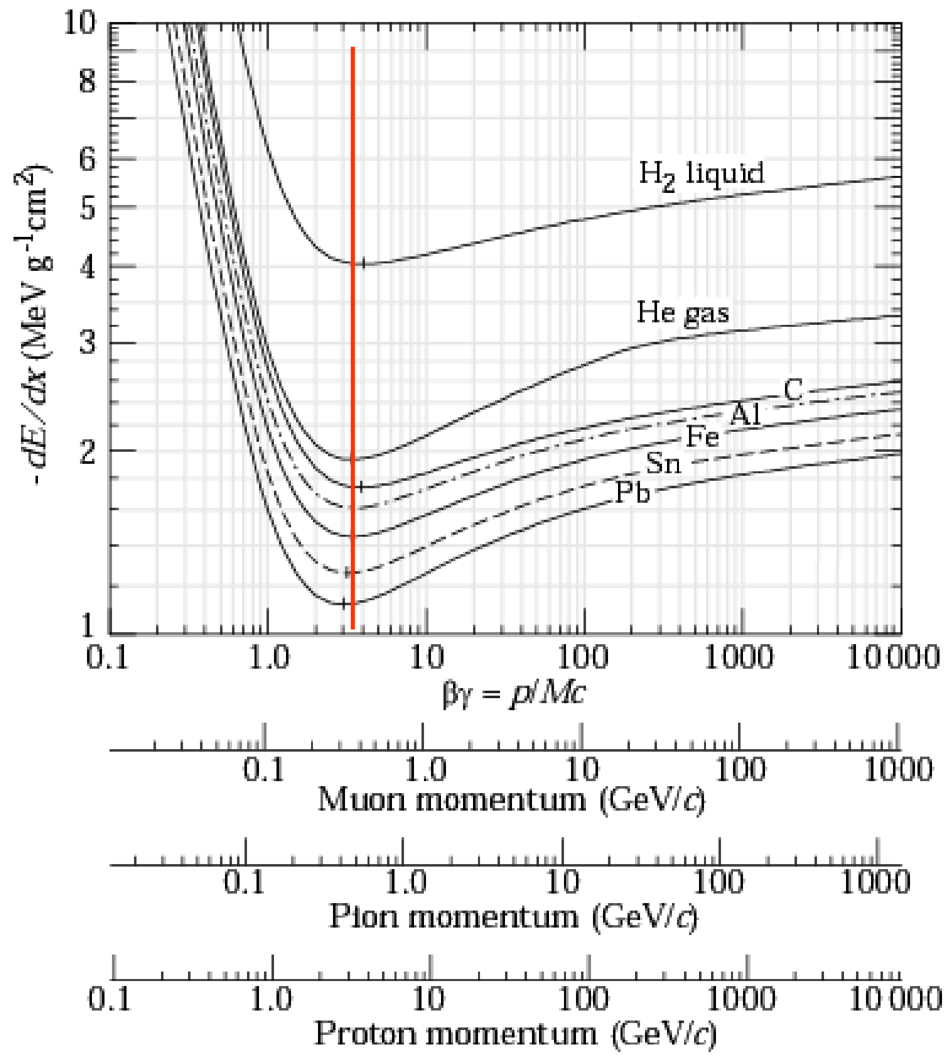
- **Signal treatment** added to intrinsic detector resolution → **Read-out electronics** !
  - Example: ATLAS LAr calorimeter
  - Ionization signal 500 ns ~ 20 LHC BXs
  - Fast shaper reduces signal to 5 LHC BXs → less pile-up but higher electronics noise
  - Choice of optimal timing varies with luminosity



After E. Garutti et al.

- Minimum at βγ ~ 3 … 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.

Q2

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 ?