Instrumentation

Content

Introduction

Part 1: Passage of particles through matter

- Charges particles, Photons, Neutrons, Neutrinos
- Multiple scattering, Cherenkov radiation, Transition radiation, dE/dx
- Radiation length, Electromagnetic showers, Nuclear Interaction length and showers, Momentum measurements.

Part 2: Particle Detection

- Ionisation detector
- Scintillation detectors
- Semiconductor detectors
- Signal processing

Goals

- Give you the understanding that detector physics is important and rewarding.
- Give the necessary background for all of you to obtain a basic understanding of detector physics; but only as a starting point, you will have use the references a lot.
- I will not try to impress you with the latest, newest and most fashionable detector development for three reasons
  - If you have the basics you can understand it yourself
  - I don’t know them
  - If I knew them I would not have time to describe them all anyway

Instrumentation

Experimental Particle Physics

Accelerators

- Luminosity, energy, quantum numbers

Detectors

- Efficiency, speed, granularity, resolution

Trigger/DAQ

- Efficiency, compression, through-put, physics models

Offline analysis

- Signal and background, physics models.

The primary factors for a successful experiment are the accelerator and detector/trigger system, and losses there are not recoverable. New and improved detectors are therefore extremely important for our field.

Instrumentation

These lectures are mainly based on seven books/documents :

(1) W.R.Leo; Techniques for Nuclear and Particle Physics Experiments. Springer-Verlag, ISBN-0-387-57280-5; Chapters 2,6,7,10.

(2 and 3)

D.E.Groom et al.,Review of Particle Physics; section: Experimental Methods and Colliders; see http://pdg.web.cern.ch/pdg/

Section 27: Passage or particles through matter

Chapter 28 : Particle Detectors.

(4) Particle Detectors; CERN summer student lectures 2002 by C.Joram, CERN. These lectures can be found on the WEB via the CERN pages, also video-taped.

(5) Instrumentation; lectures at the CERN CLAF shool of Physics 2001 by O.Ullaland, CERN. The proceeding is available via CERN.

(6) K.Kleinknecht; Detectors for particle radiation. Cambridge University Press, ISBN 0-521-64854-8.

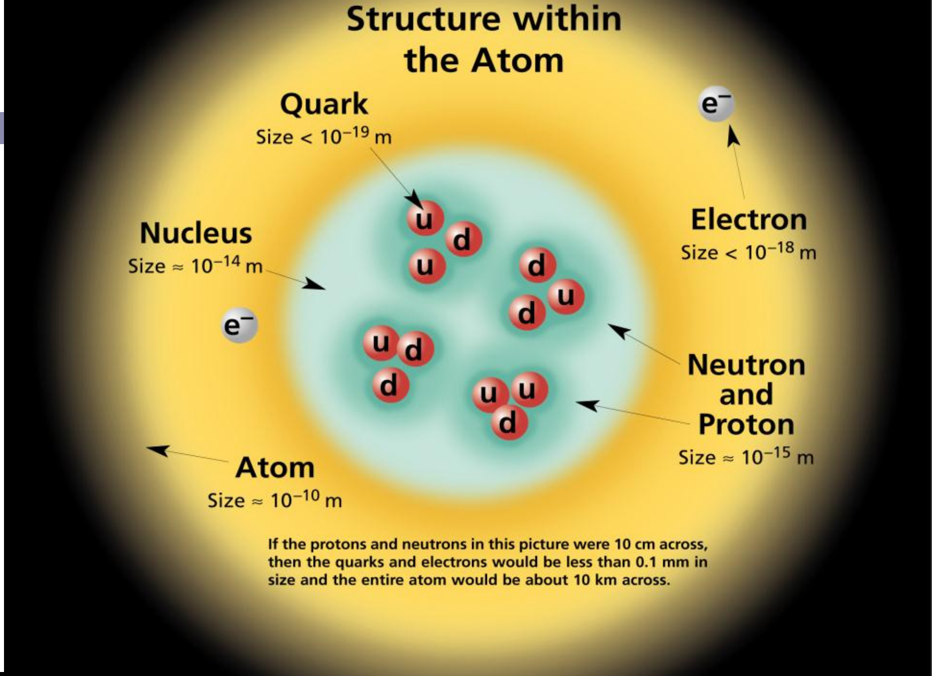
(7) G.F.Knoll; Radiation Detection and Measurement. John Wiley & Sons, ISBN 0-471-07338-5

In several cases I have included pictures from (4) and (5) and text directly in my slides (indicated in my slides when done).

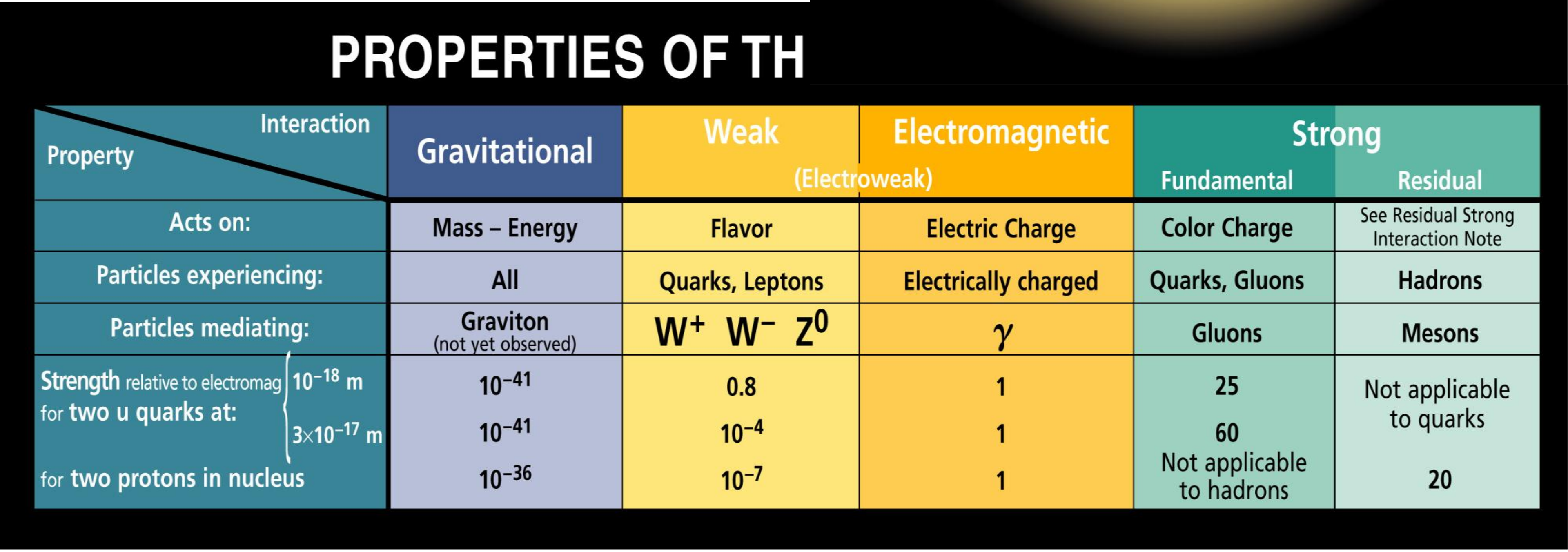
I would recommend all those of you needing more information to look at these sources of wisdom, and the references.

Concentrate on electromagnetic forces since a combination of their strength and reach make them the primary responsible for energy loss in matter.

For neutrons, hadrons generally and neutrinos other effects obviously enter.



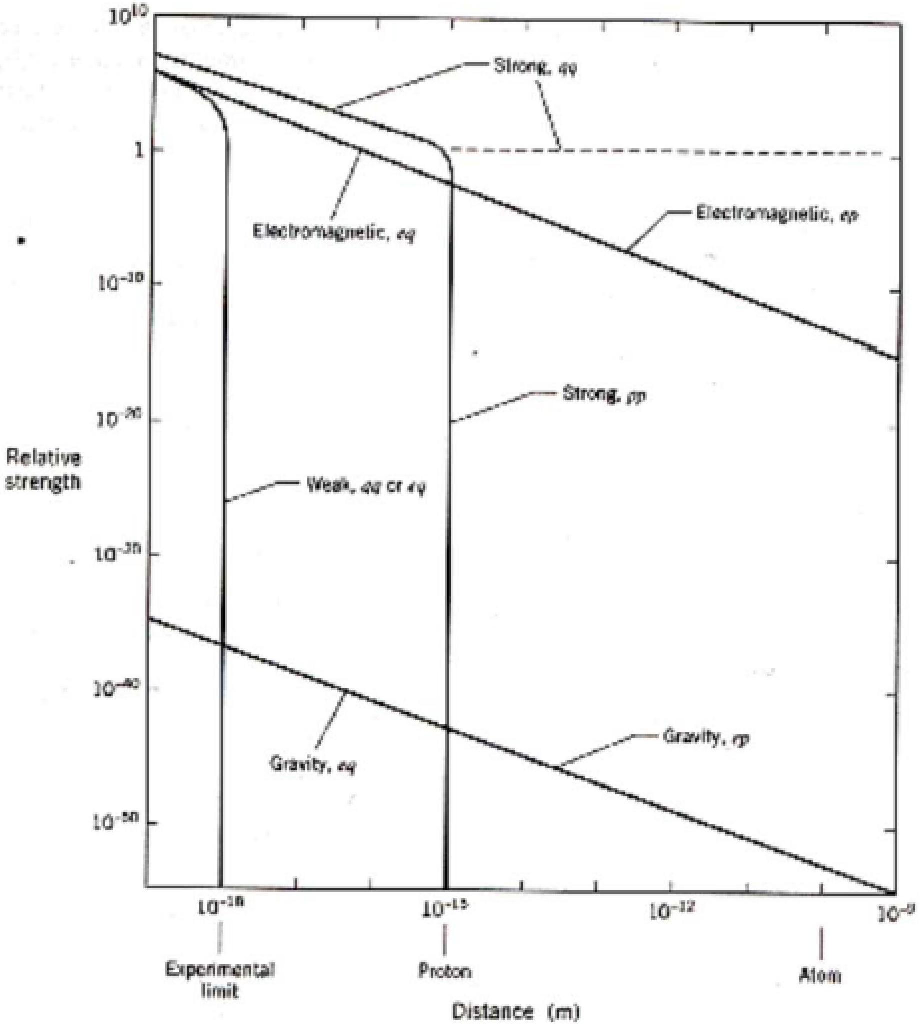
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



PROPERTIES OF TH

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Strength versus distance



- At atomic distances only EM & gravity have sizable strengths
- EM is ~40 orders of magnitude stronger than gravity
- If quarks could be separated force would be enormous (see dashed line)
- At proton size distances strong force turns on & becomes ~ 100 times stronger than EM force
- At distances ~ 1/1000 of proton size weak force turns on abruptly

Heavy charged particles

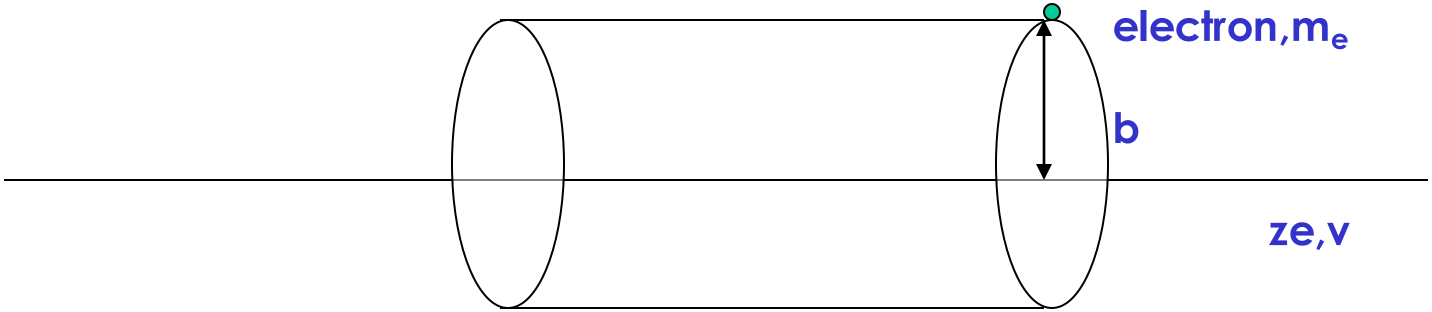
Heavy charged particles transfer energy mostly to the atomic electrons, ionising them. We will later come back to not so heavy particles, in particular electrons/positrons.

Usually the Bethe Bloch formally is used to describe this - and most of features of the Bethe Bloch formula can be understood from a very simple model :

1) Let us look at energy transfer to a single electron from heavy charged particle passing at a distance b

2) Let us multiply with the number of electrons passed

3) Let us integrate over all reasonable distances b



The impulse transferred to the electron will be :
The integral is solved by using Gauss' law over an infinite cylinder (see fig) :

$$I = \int F dt = e \int E_{\perp} \frac{dx}{v} = \frac{2ze^2}{bv}$$

The energy transfer is then :

$$\Delta E(b) = \frac{I^2}{2m_e}$$

The transfer to a volume dV where the electron density is N_e is therefore :

$$-dE(b) = \Delta E(b) N_e dV ; dV = 2\pi b db dx$$

The energy loss per unit length is given by :

- b_{min} is not zero but can be determined by the maxium energy transferred in a head-on collision
- b_{max} is given by that we require the perturbation to be short compared to the period (1/v) of the electron.

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

Finally we end up with the following which should be compared to Bethe Bloch formula below :

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4}{m_e v^2} N_e \ln \frac{\gamma^2 m_e v^3}{z e^2 \overline{v}}$$

Note :
dx in Bethe Bloch includes density (g cm^{-2})

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

Bethe Bloch parametrizes over momentum transfers using I (the ionisation potential) and T_{max} (the maximum transferred in a single collision) :

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

The correction δ describe the effect that the electric field of the particle tends to polarize the atoms along it part, hence protecting electrons far away (this leads to a reduction/plateau at high energies).

The curve has minimum at β=0.96 ($\beta\gamma$=3.5) and increases slightly for higher energies; for most practical purposed one can say the curve depends only on β (in a given material). Below the Minimum Ionising point the curve follows $\beta^{-5/3}$.

At low energies other models are useful (as shown in figure).

The radiative losses at high energy we will discuss later (in connection with electrons where they are much more significant at lower energies).

Bethe Bloch basics

A more complete description of Bethe Bloch and also Cherenkov radiation and Transition Radiation – starting from the electromagnetic interaction of a particle with the electrons and considering the energy of the photon exchanged – can be found in ref. 6 (Kleinknecht).

Depending on the energy of the photon one can create Cherenkov radiation (depends on velocity of particle wrt speed of light in the medium), ionize (Bethe Bloch energy loss when integration from the ionisation energy to maximum as on previous page), or create Transition Radiation at the border of two absorption layers with different materials.

See also references to articles of Allison and Cobb in the book.

Processed as function of photon energy

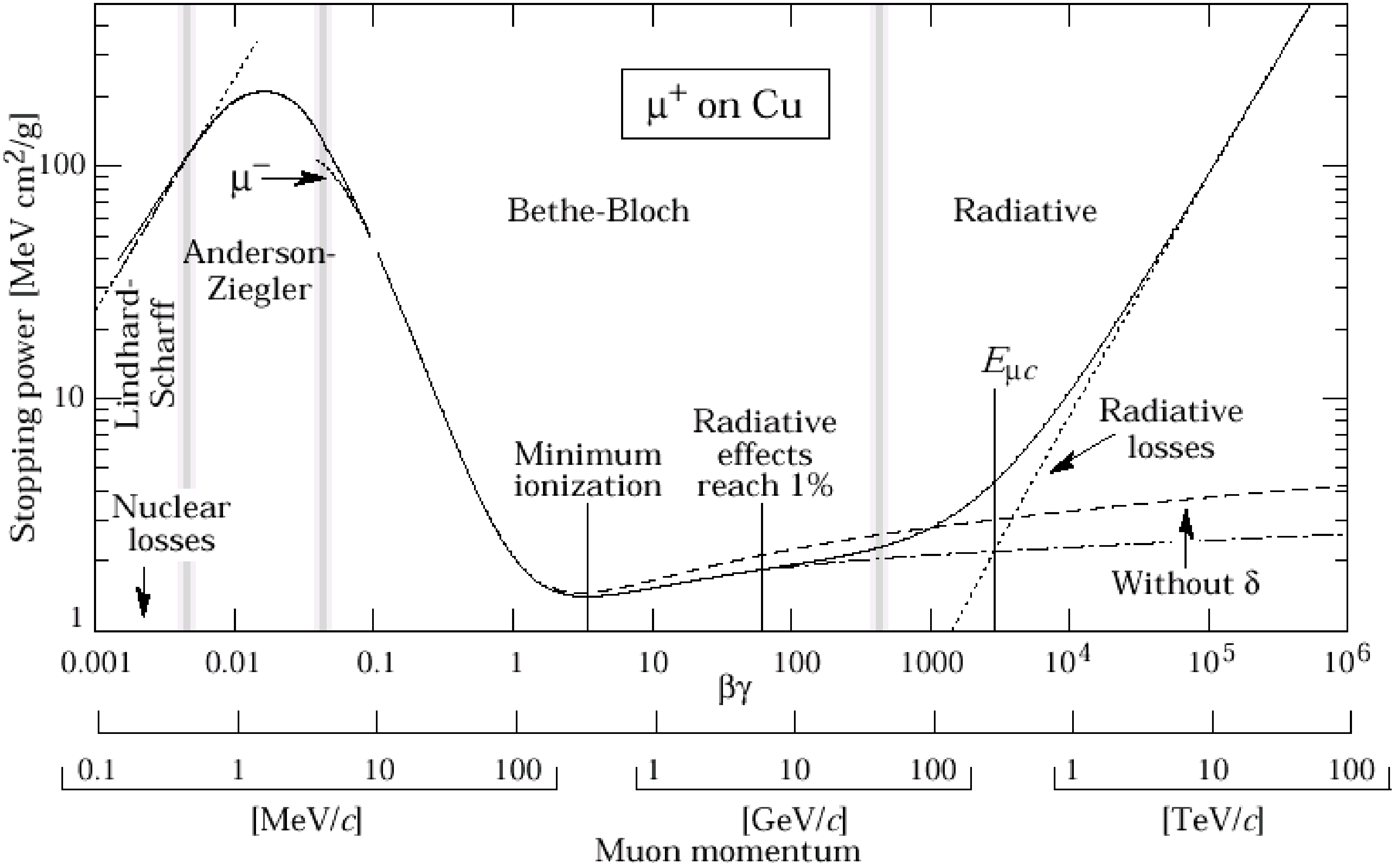
Consider a particle in a medium emitting a photon:

- particle: mass m, velocity $\vec{v}=\vec{\beta}\cdot c$, energy E, momentum $\vec{p}$
- medium: refractive index n, dielectric constant $\varepsilon=\varepsilon_1+i\varepsilon_2$, & $n^2=\varepsilon_1$
- photon: energy $\hbar\omega$, momentum $\hbar\vec{k}$

☐ Depending on $\hbar\omega$ different processes occur:

1) For $\hbar\omega < E_{excitation}$ [optical region] $\varepsilon > 1$ (real) → em shock wave
   - → θ_c real for $v > c/n$
   - → emission of real photon is possible if particle velocity is larger than phase velocity c/n of light (Cherenkov effect)
2) For $2\ eV < \hbar\omega < 5\ keV$, ε is complex with $\varepsilon_1<1$, $\varepsilon_2>0$
   - → production of virtual photons only
   - → excitation and ionization of medium
3) For $\hbar\omega > 5keV$ absorption becomes small: $\varepsilon_2<<1$, but $\varepsilon_1<1$
   - → Threshold velocity for Cherenkov effect is larger than c
   - → Radiation is emitted below this threshold if medium has discontinuities → transition radiation

Heavy charges particles



Heavy charged particles

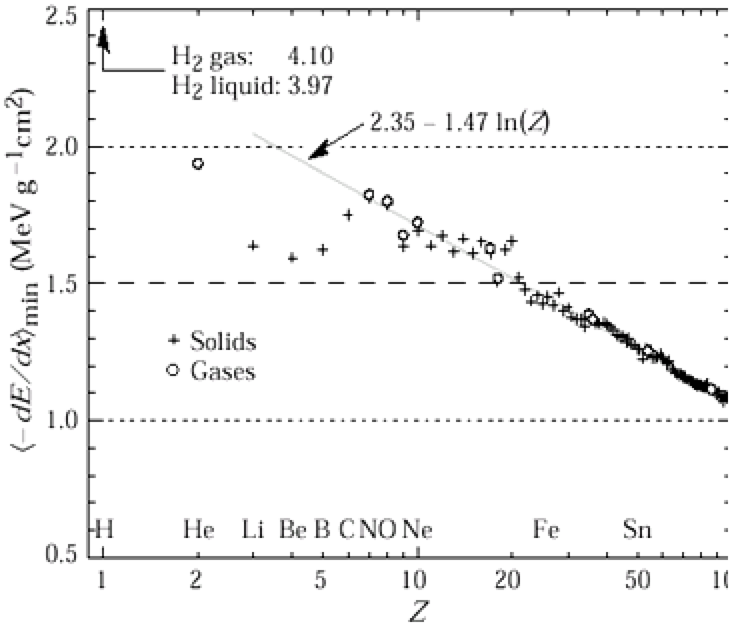
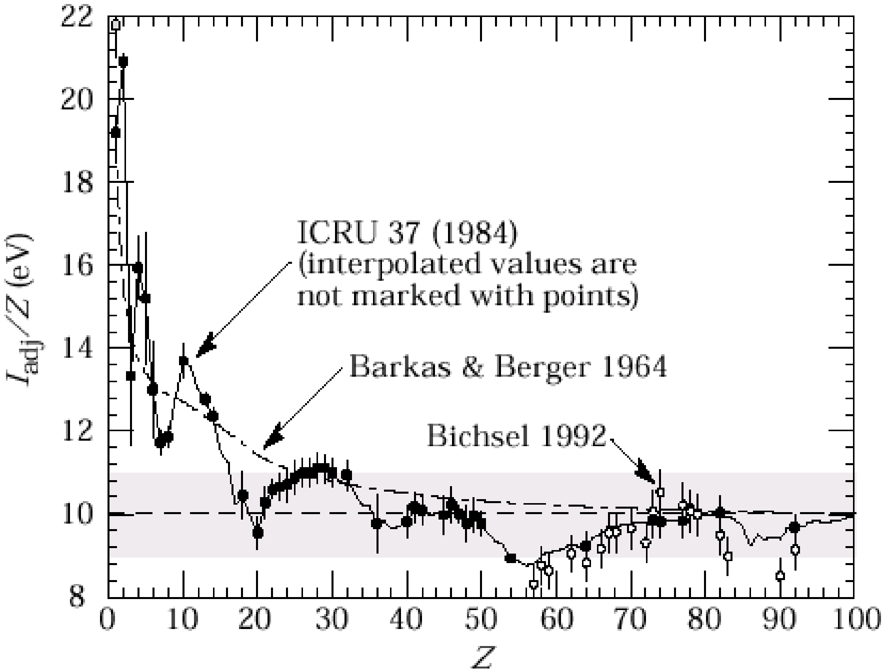
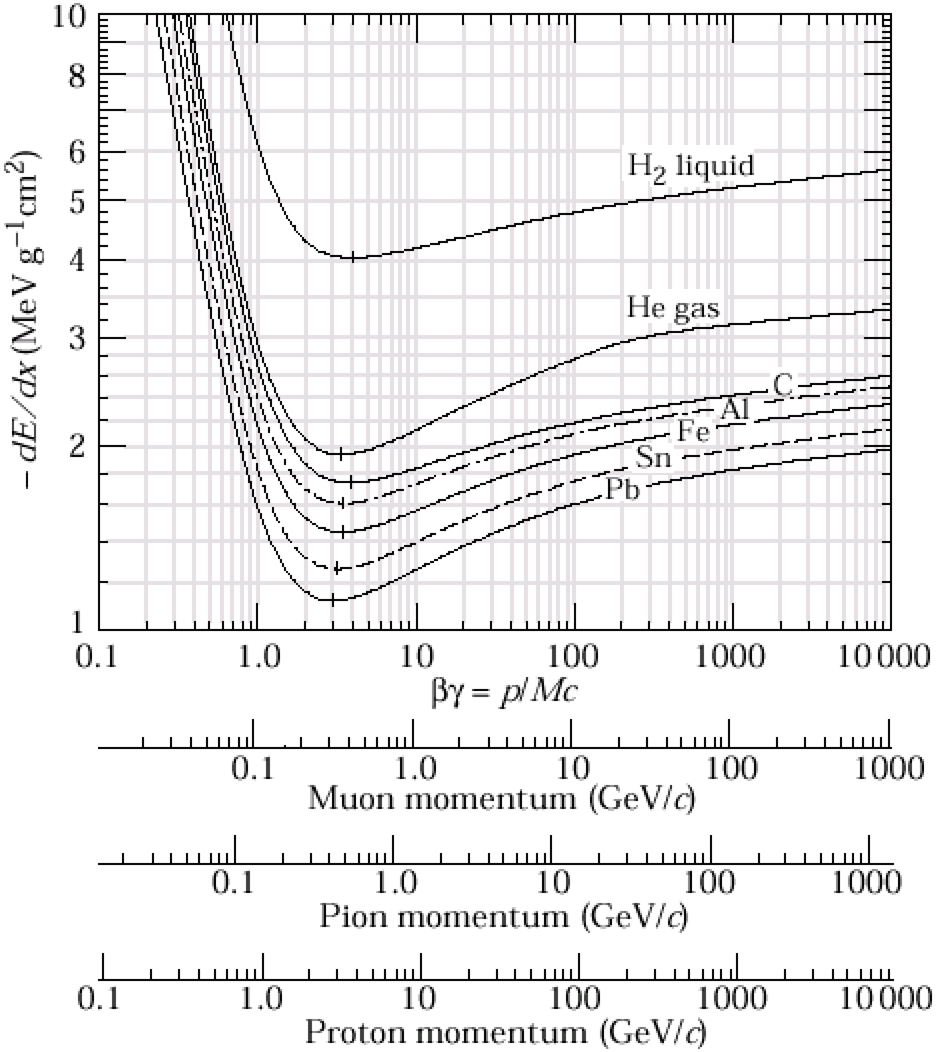


Figure 26.2: Stopping power at minimum ionization for the chemical elements. The straight line is fitted for $Z > 6$. A simple functional dependence on Z is not to be expected, since $\langle -dE/dx \rangle$ also depends on other variables.

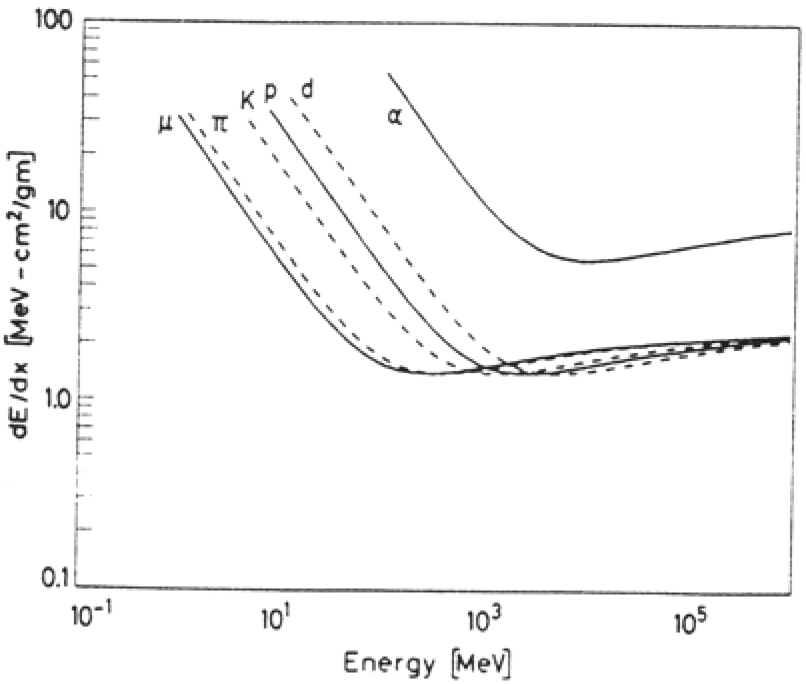
The ionisation potential (not easy to calculate):



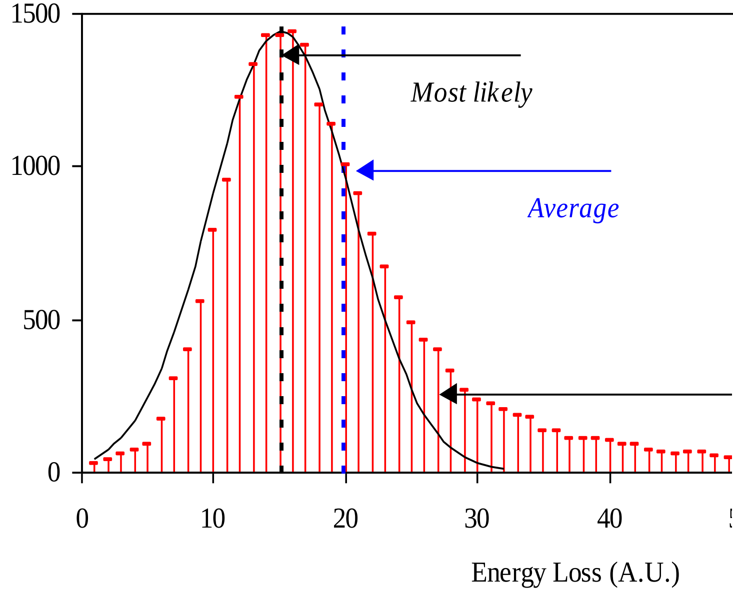
Heavy charged particles

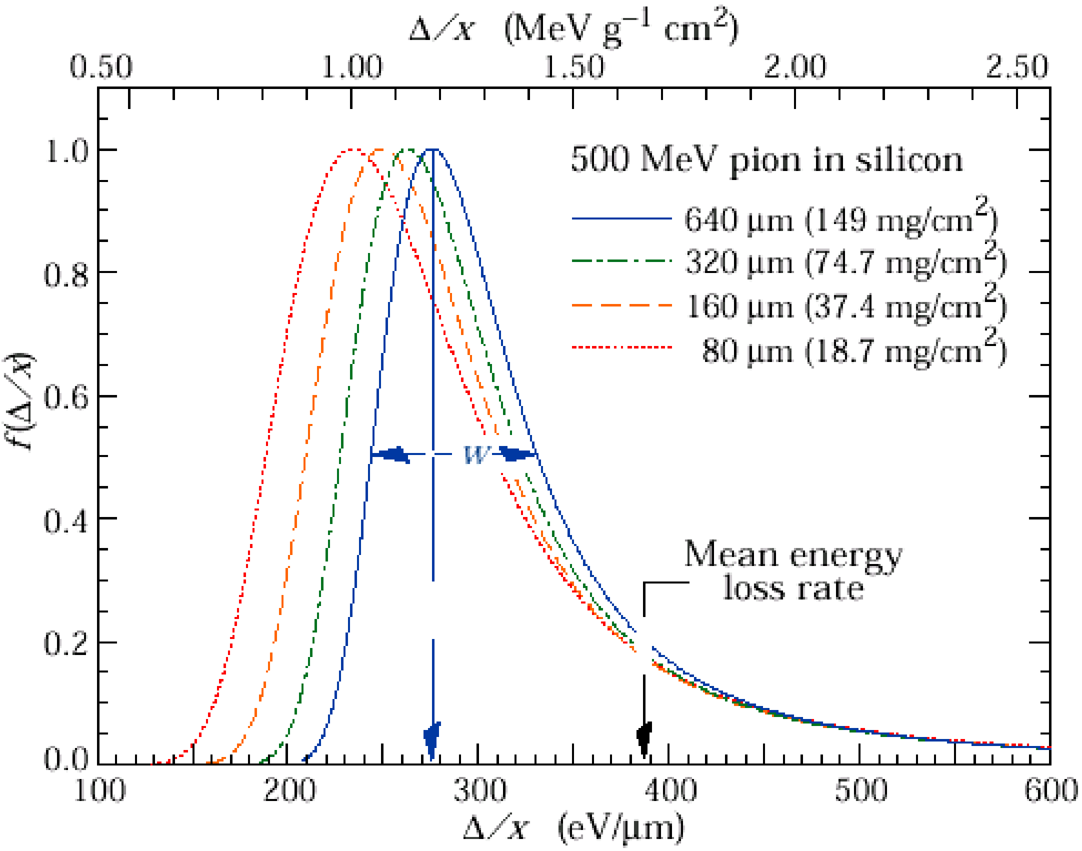


Since particles with different masses have different momenta for same β



Heavy charged particles

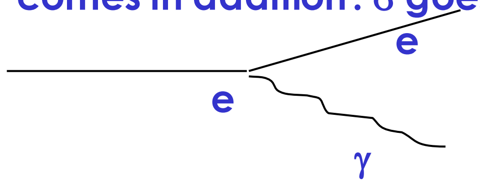


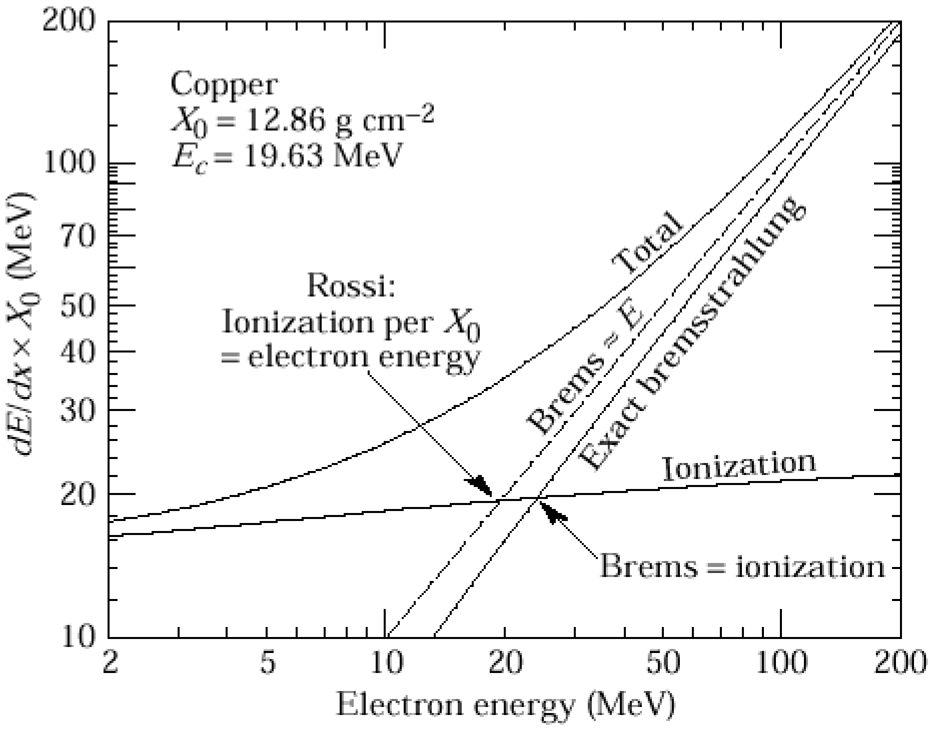


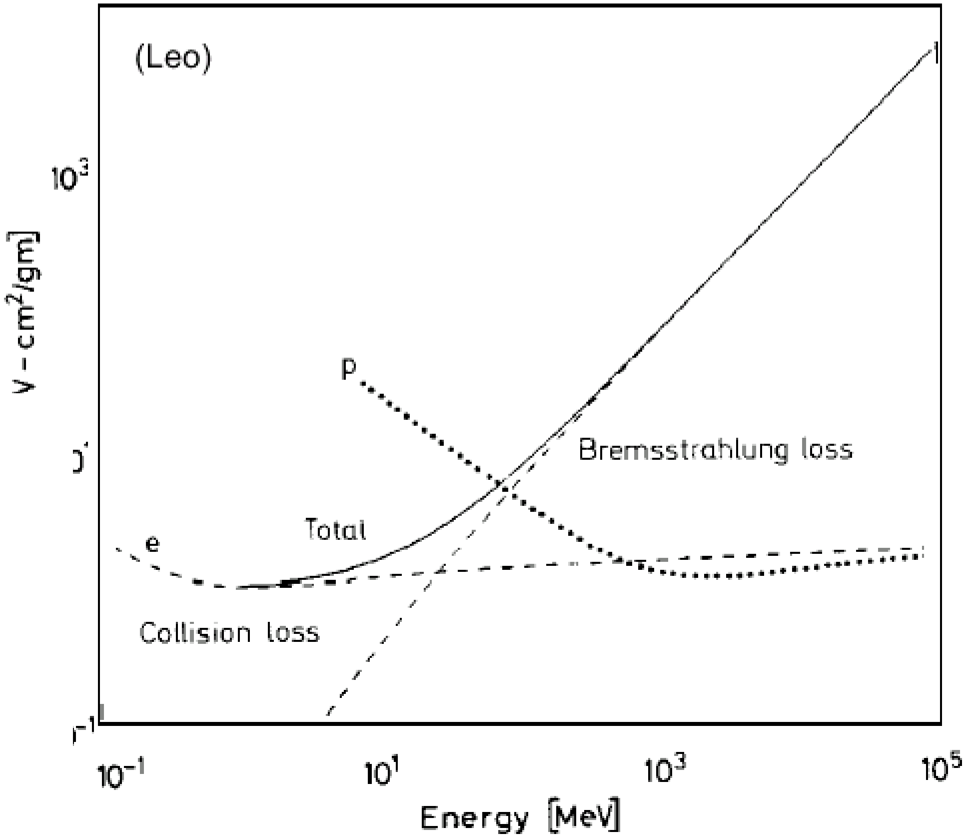
While Bethe Bloch describes the average energy deposition, the probability distribution is described by a Landau distribution . Other functions are ofter used : Vavilov, Bichsel etc. In general these a skewed distributions tending towards a Gaussian when the energy loss becomes large (thick absorbers). One can use the ratio between energy loss in the absorber under study and T_{max} from Bethe Bloch to characterize thickness.

Electrons and Positrons

- Electrons/positrons; modify Bethe Bloch to take into account that incoming particle has same mass as the atomic electrons
- Bremsstrahlung in the electrical field of a charge Z comes in addition : σ goes as $1/m^2$







The critical energy is defined as the point where the ionisation loss is equal the bremsstrahlung loss.

Electrons and Positrons

The differential cross section for Bremsstrahlung (ν : photon frequency) in the electric field of a nucleus with atomic number Z is given by (approximately):

$$d\sigma \propto Z^2 \frac{d\nu}{\nu}$$

The bremsstrahlung loss is therefore :
where the linear dependence is shown.
The φ function depends on the material (mostly); and for example the atomic number as shown.
N is atom density of the material (atoms/cm^3).
Bremsstrahlung in the field of the atomic electrons must be added (giving Z^2+Z).

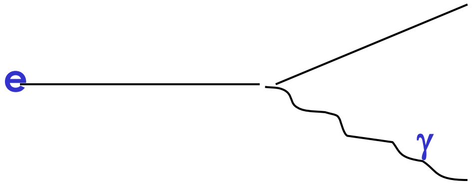
$$-(\frac{dE}{dx}) = N \int_0^{\nu_0 = E_o/h} h\nu \frac{d\sigma}{d\nu} d\nu = N E_0 \phi(Z^2)$$

A radiation length is defined as thickness of material where an electron will reduce it energy by a factor 1/e; which corresponds to 1/Nϕ as shown on the right (usually called χ_0).

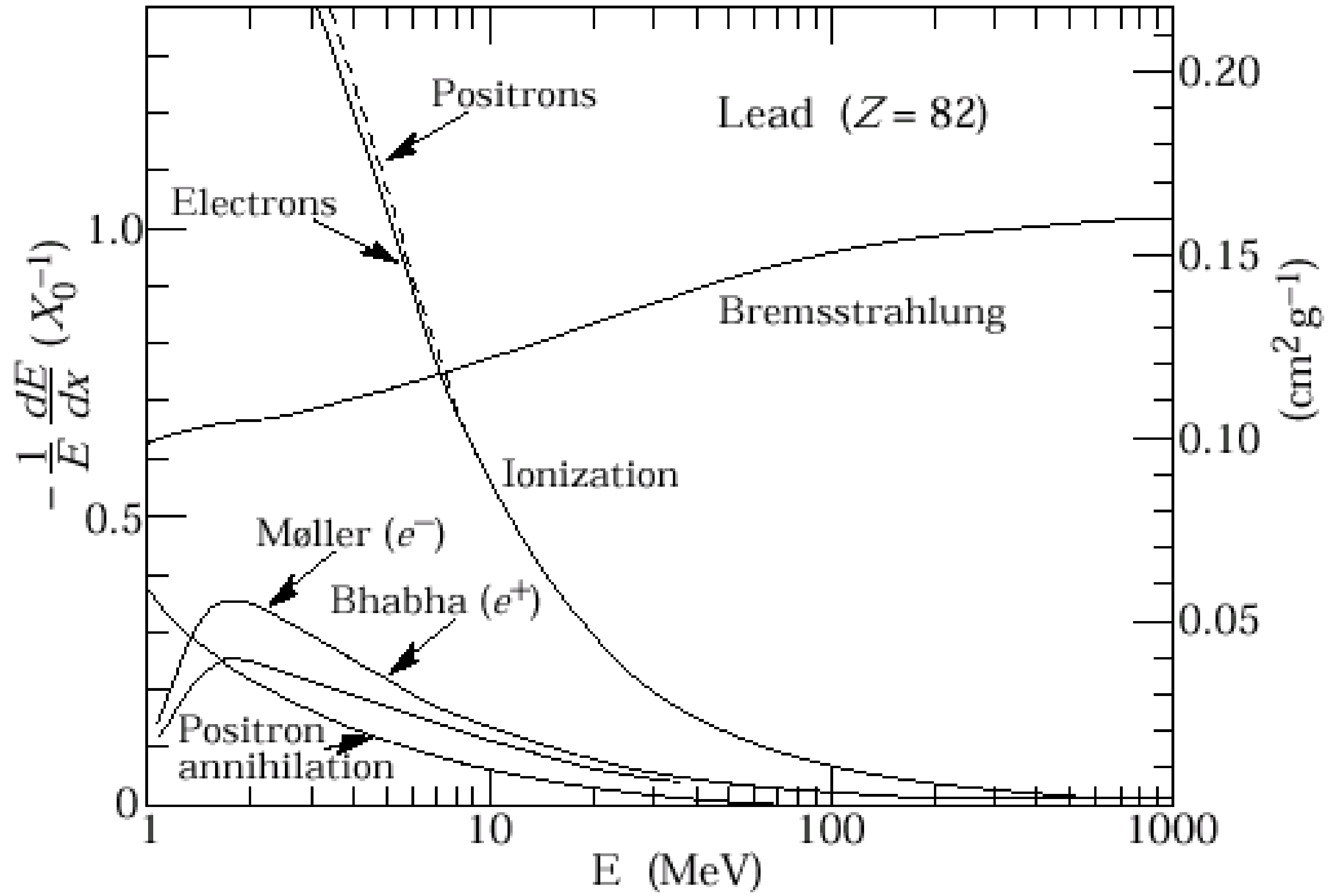
$$-(\frac{dE}{E}) = N\phi dx$$

$$giving$$

$$E = E_0 \exp(\frac{-x}{1/N\phi})$$



Electrons and Positrons



Electrons and Positrons

Radiation length parametrisation :

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 \left[L_{\rm rad} - f(Z) \right] + Z \, L'_{\rm rad} \right\} .$$

Element	Z	$L_{\rm rad}$	$L'_{\rm rad}$
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	> 4	$\ln(184.15\, Z^{-1/3})$	$\ln(1194\, Z^{-2/3})$

A formula which is good to 2.5% (except for helium) :

$$X_0 = \frac{716.4 \ {\rm g \ cm^{-2}} \ A}{Z(Z+1) \ln(287/\sqrt{Z})}$$

A few more real numbers (in cm) : air = 30000cm, scintillators = 40cm, Si = 9cm, Pb = 0.56cm, Fe = 1.76 cm.

Photons

Photons important for many reasons :

- Primary photons
- Created in bremsstrahlung
- Created in detectors (de-excitations)
- Used in medical applications, isotopes

They react in matter by transferring all (or most) of their energy to electrons and disappearing. So a beam of photons do not lose energy gradually; it is attenuated in intensity (only partly true due to Compton scattering).

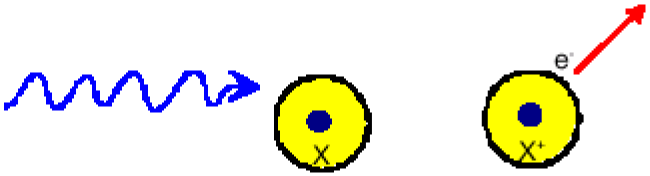
Photons

Three processes :

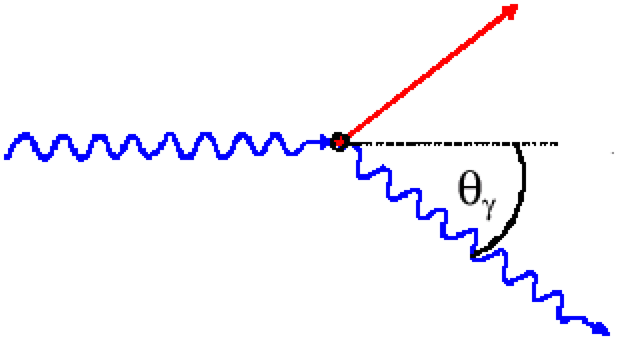
Photoelectric effect (Z^5); absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.

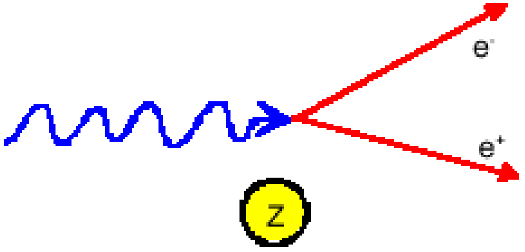
Compton scattering (Z); scattering of an electron again a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc) and for energies above a few MeV 90% of the energy is transferred (in most cases).

Pair-production (Z^2+Z); essentially bremsstrahlung again with the same machinery as used earlier; threshold at 2 m_e = 1.022 MeV. Dominates at a high energy.



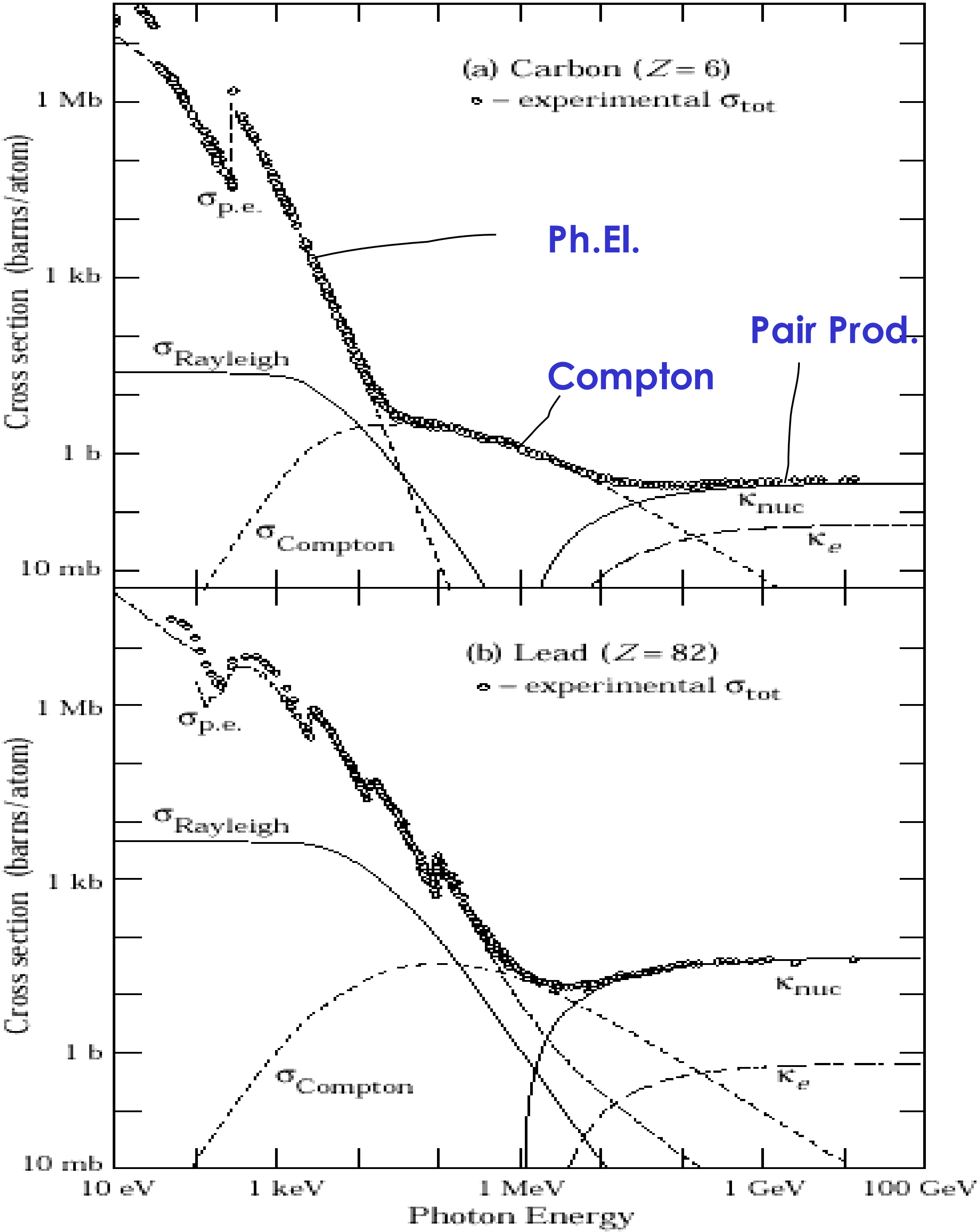
$$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$$





Plots from C.Joram

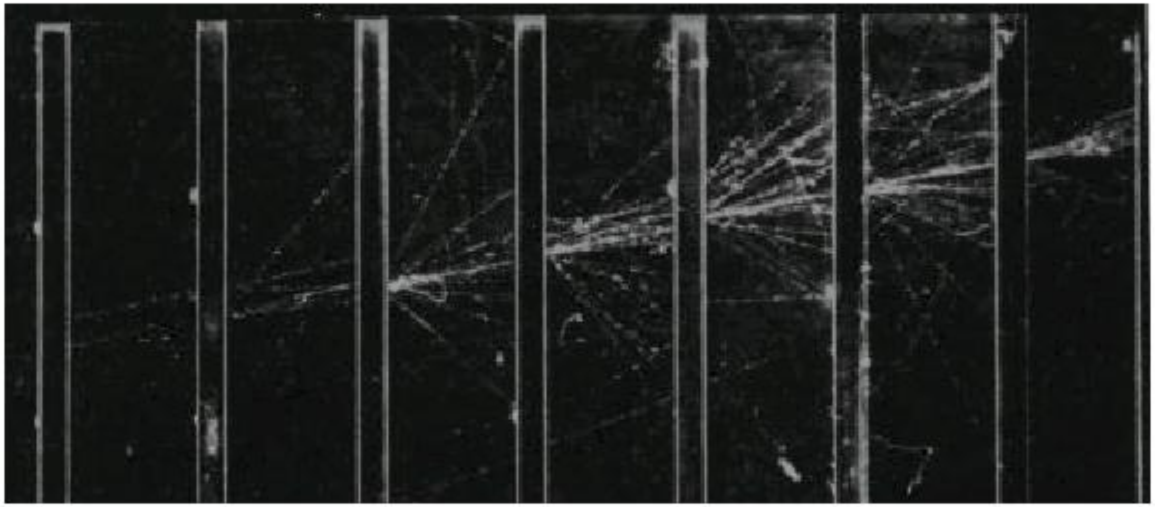
Photons



Considering only the dominating effect at high energy, the pair production cross-section, one can calculate the mean free path of a photon based on this process alone and finds :

$$Photon_{mfp} = \frac{\int x \exp(-N\sigma_{pair} x)dx}{\int \exp(-N\sigma_{pair} x)dx} \cong \frac{9}{7}\chi_0$$

Electromagnetic calorimeters

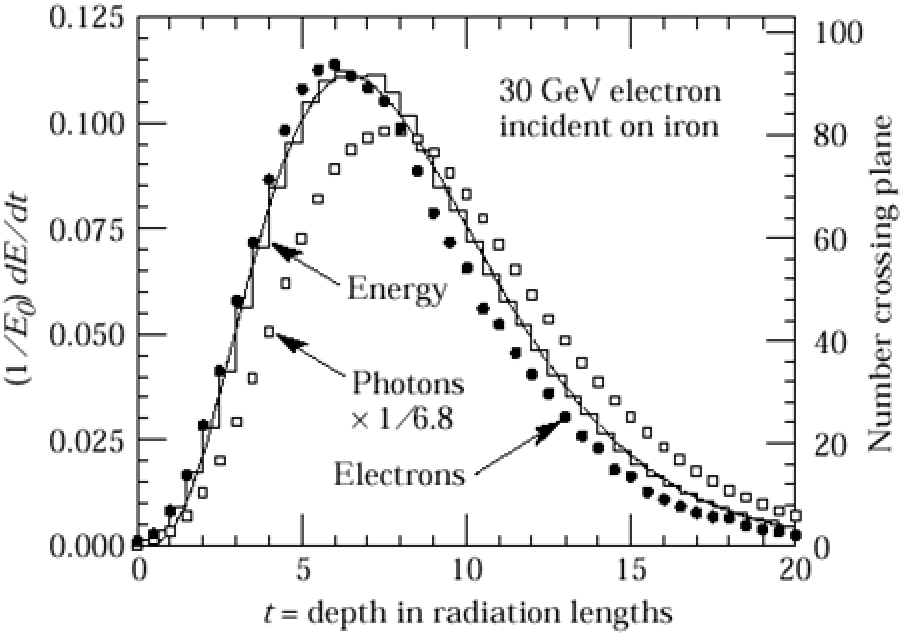


Electron shower in a cloud chamber with lead absorbers

From C.Joram

Considering only Bremsstrahlung and Pair Production with one splitting per radiation length (either Brems or Pair) we can extract a good model for EM showers.

Electromagnetic calorimeters



More :

Longitudinal shower development:

$$\frac{dE}{dt} \propto t^{\alpha} e^{-t}$$

Shower maximum at $t_{\max} = \ln \frac{E_0}{E_c} \frac{1}{\ln 2}$

95% containment $t_{95\%} \approx t_{\max} + 0.08Z + 9.6$

Example: 100 GeV in lead glass (E_c=11.8 MeV) → $t_{max} \approx 13$, $t_{95\%} \approx 23$

Size of a calorimeters grows only logarithmically with E

Text from C.Joram

$$N(t) = 2^{t} \qquad E(t)/\,particle = E_0 \cdot 2^{-t}$$

Process continues until $E(t)<E_c$

$$t_{\max} = \frac{\ln E_0/E_c}{\ln 2} \qquad N^{total} = \sum_{t=0}^{t_{\max}} 2^{t} = 2^{(t_{\max}+1)} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

After $t = t_{max}$ the dominating processes are ionization, Compton effect and photo effect → absorption.

Text from C.Joram

Electromagnetic calorimeters

The total track length :

$$T \propto N_{tracks}\chi_0 = \frac{E_0}{E_C}\chi_0$$

Intrinsic resolution :

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(T)}{T} \propto \frac{1}{\sqrt{T}} \propto \frac{1}{\sqrt{E}}$$

Also spatial and angular resolution scale like $1/\sqrt{E}$

Text from C.Joram

More general:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term

Constant term

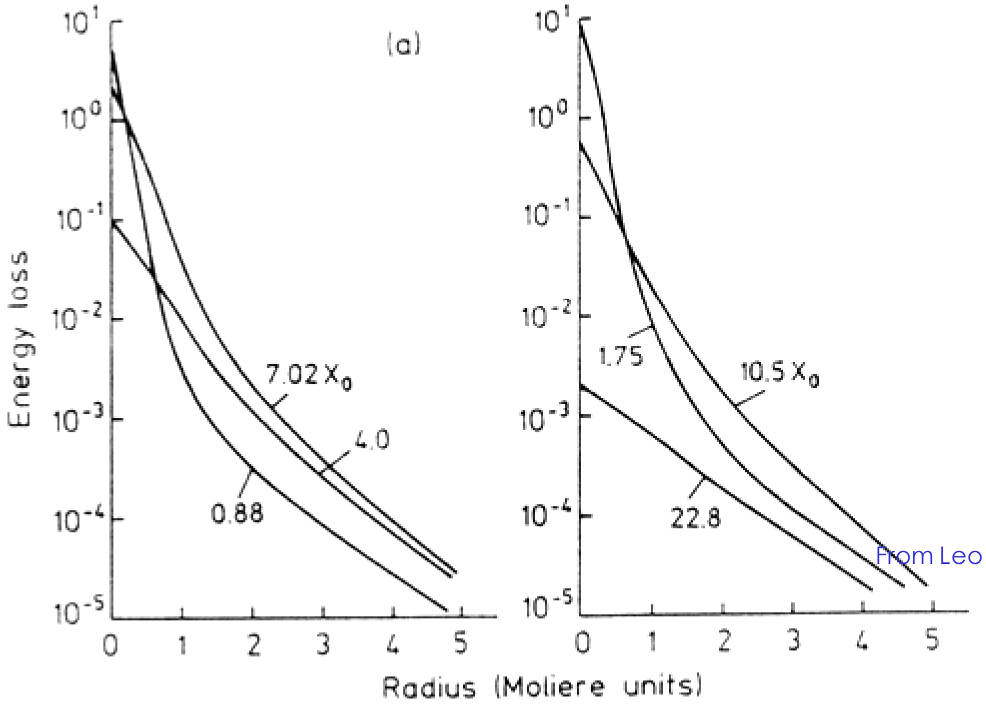
Noise term

Inhomogenities
Bad cell inter-calibration
Non-linearities

Quality factor !

Electronic noise
radioactivity
pile up

Electromagnetic calorimeters



From Leo

Transverse shower development:

95% of the shower cone is located in a cylinder with radius 2 R_M $R_M = \frac{21\,\text{MeV}}{E_c} X_0 \quad [g/cm^2]$

Example: lead glass R_M= 1.8 X_0 ≈ 3.6 cm (depends on glass type)

Text from C.Joram

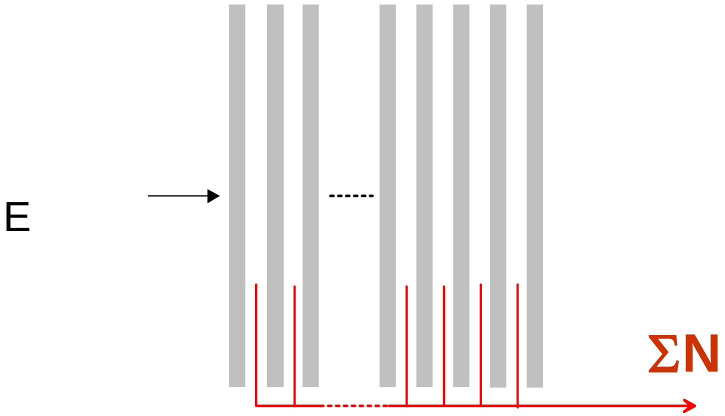
Sampling Calorimeter

A fraction of the total energy is sampled in the active detector

Particle absorption

Shower sampling

is separated.



Active detector :

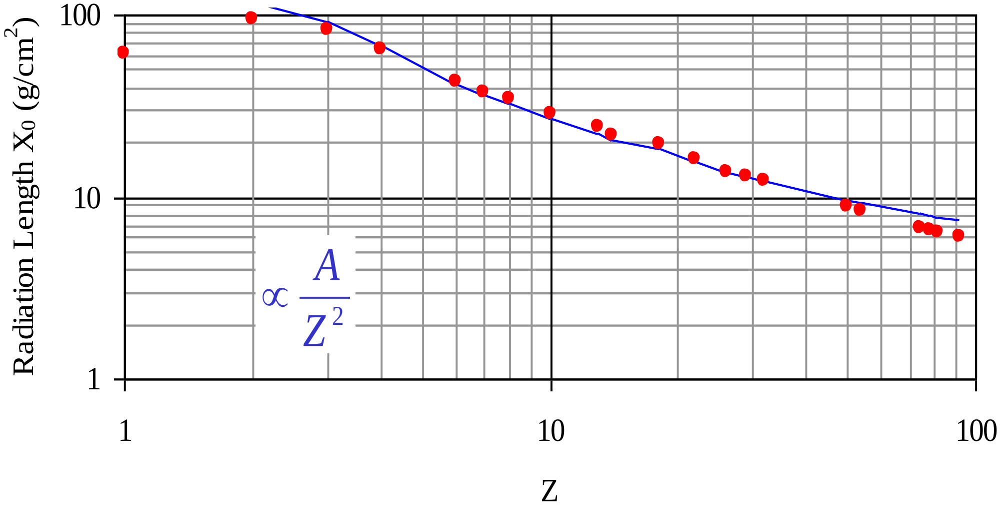
Scintillators

Ionization chambers

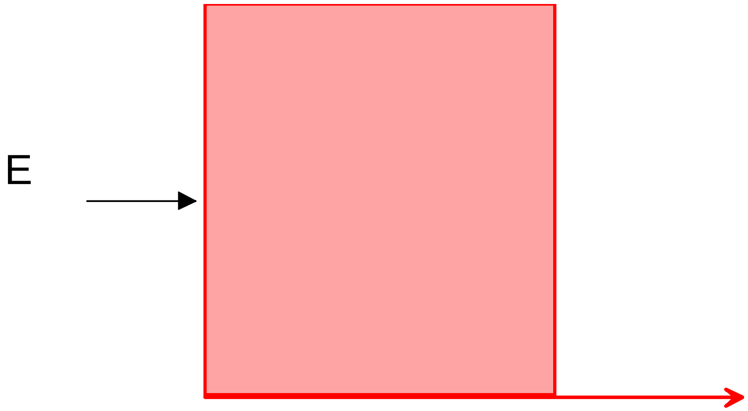
Wire chambers

Silicon

$$\sum N \propto E \rightarrow \frac{\sigma(E)}{E} \geq 10\% \text{ at 1 GeV}$$



Homogeneous Calorimeter
The total detector is the active detector.



N ∝ E

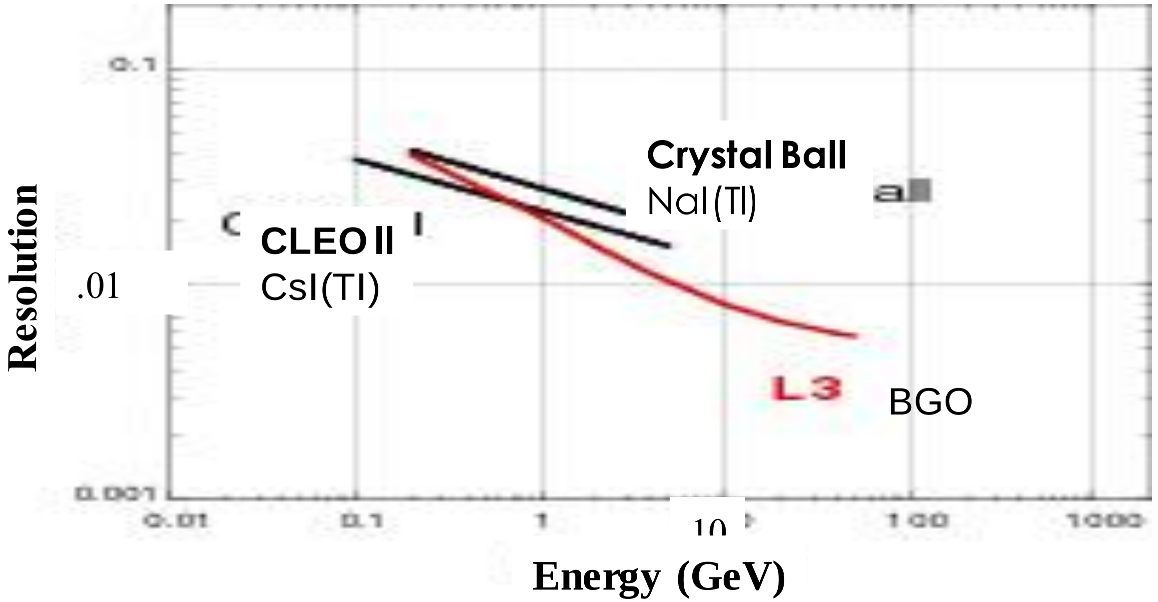
σ(E) ~ Limited by photon statistics

$$\frac{\sigma(E)}{E} \approx 1-2\%$$ at 1 GeV

N

Crystal		BGO	CsI:Tl	CsI	PWO	NaI:Tl
Density	g/cm^3	7.13	4.53	4.53	8.26	3.67
Radiation length	cm	1.12	1.85	1.85	0.89	2.59
Wave length	nm	480	565	310	420	410
Light yield	% of NaI	10	85	7	0.2	100
Decay time	ns	300	1000	6+35	5+15+100	250
Temp. dependence	$\%/^{o}C$ @18^{o}	-1.6	0.3	-0.6	-1.9	0
Refr. index		2.15	1.8	1.8	2.29	1.85

E. Longo, Calorimetry with Crystals, submitted to World Scientific, 1999



Neutrons

Neutrons have no charge, i.e. their interaction is based only on strong (and weak) nuclear force.

To detect neutrons, we have to create charged particles.

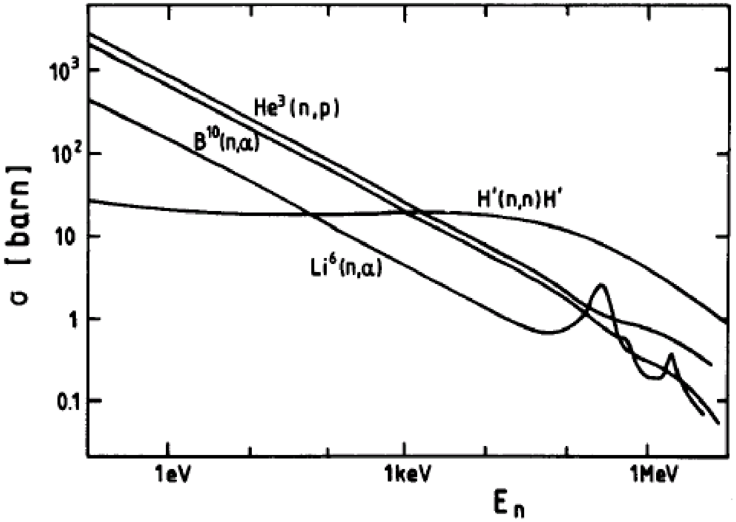
Possible neutron conversion and elastic reactions

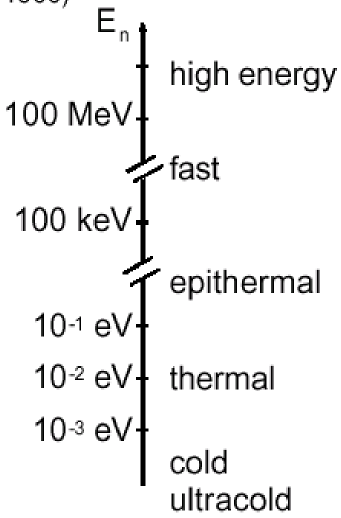
- $n + {}^6Li \rightarrow \alpha + {}^3H$
- $n + {}^{10}B \rightarrow \alpha + {}^7Li$
- $n + {}^3He \rightarrow p + {}^3H$

$\Big\}$ $E_n < 20$ MeV

- $n + p \rightarrow n + p$ $\quad E_n < 1$ GeV

(H. Neuert, Kernphysikalische Messverfahren, G. Braun Verlag, 1966)





In addition there are

- neutron induced fission $\quad E_n \approx E_{th} \approx \frac{1}{40}$ eV
- hadronic cascades (see below) $\quad E_n > 1$ GeV

Text from C.Joram

Absorption length and Hadronic showers

Text from C.Joram

Hadronic + electromagnetic component

↓ ↓

charged pions, protons, kaons ….

Breaking up of nuclei

(binding energy),

neutrons, neutrinos, soft γ's

muons …. → invisible energy

neutral pions → 2γ →

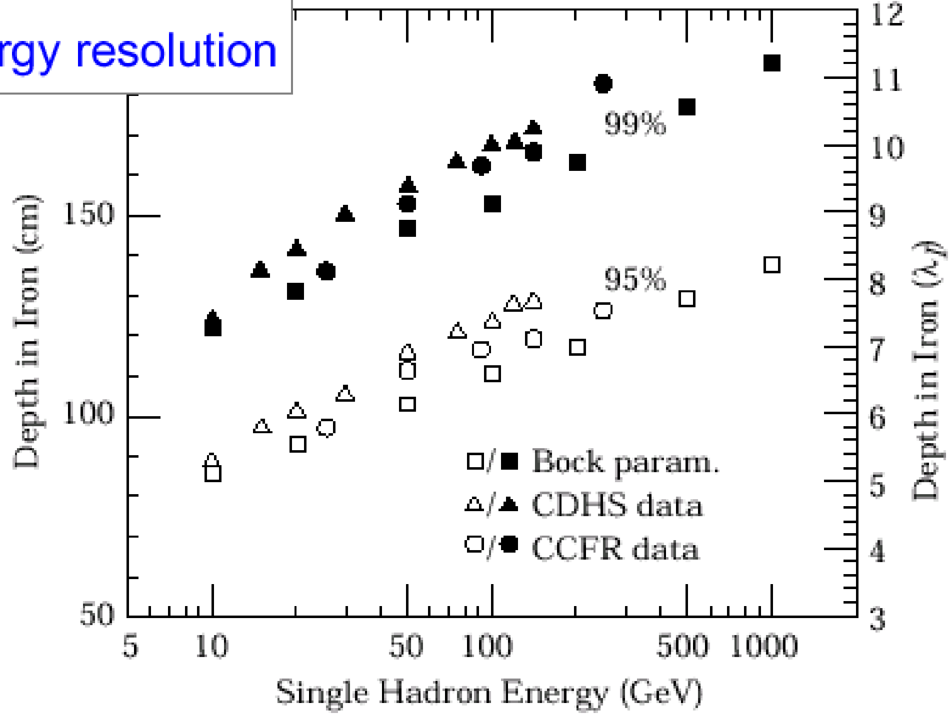
electromagnetic cascade

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

example 100 GeV: $n(\pi^0) \approx 18$

Large energy fluctuations → limited energy resolution

Define hadronic absorption and interaction length by the mean free path (as we could have done for χ_0) using the inelastic or total cross-section for a high energy hadrons (above 1 GeV the cross-sections vary little for different hadrons or energy).



Longitudinal shower development

Text from C.Joram

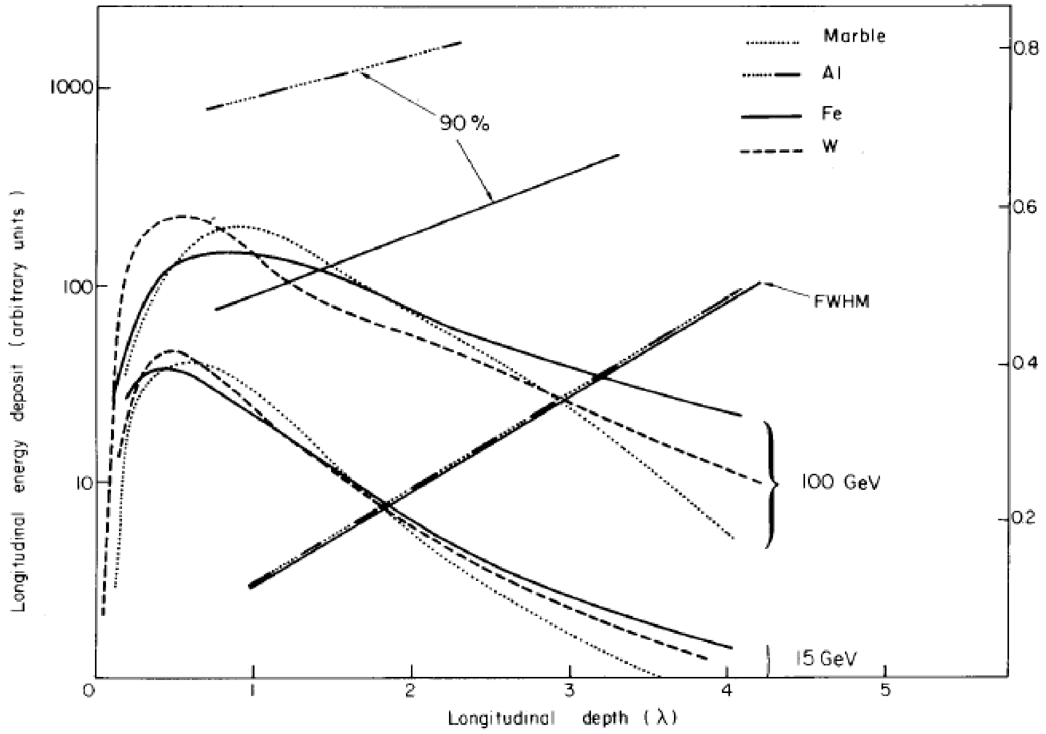
$$t_{\max}(\lambda_I) \approx 0.2 \ln E[GeV] + 0.7$$

$$t_{95\%} \approx a \ln E + b$$

For Iron: a = 9.4, b=39

E =100 GeV

→ $t_{95\%} \approx$ 80 cm



(C. Fabjan, T. Ludlam, CERN-EP/82-37)

		A	ρ [g/cm³]	X_0 [g/cm²]	λ_a [g/cm²]
Hydrogen (gas)	1	1.01	0.0899 (g/l)	63	50.8
Helium (gas)	2	4.00	0.1786 (g/l)	94	65.1
Beryllium	4	9.01	1.848	65.19	75.2
Carbon	6	12.01	2.265	43	86.3
Nitrogen (gas)	7	14.01	1.25 (g/l)	38	87.8
Oxygen (gas)	8	16.00	1.428 (g/l)	34	91.0
Aluminium	13	26.98	2.7	24	106.4
Silicon	14	28.09	2.33	22	106.0
Iron	26	55.85	7.87	13.9	131.9
Copper	29	63.55	8.96	12.9	134.9
Tungsten	74	183.85	19.3	6.8	185.0
Lead	82	207.19	11.35	6.4	194.0
Uranium	92	238.03	18.95	6.0	199.0

Neutrinos

Neutrinos interact only weakly → tiny cross-sections

For their detection we need again first a charged particle.

Possible detection reactions:

- $\nu_\ell + n \rightarrow \ell^- + p \quad \ell = e, \mu, \tau$
- $\bar{\nu}_\ell + p \rightarrow \ell^+ + n \quad \ell = e, \mu, \tau$

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm^2 (per nucleon, $E_n \approx$ few MeV).

→ detection efficiency $\varepsilon_{\det} = \sigma \cdot N^{surf} = \sigma \cdot \rho \frac{N_A}{A} d$

1 m Iron: $\varepsilon_{\det} \approx 5 \cdot 10^{-17}$

Neutrino detection requires big and massive detectors (ktons) and high neutrino fluxes.

In collider experiments fully hermetic detectors allow to detect neutrinos indirectly:

- Sum up all visible energy and momentum.
- Attribute missing energy and momentum to neutrino.

Text from C.Joram

Summary of reactions with matter

The basic physics has been described :

- Mostly electromagnetic (Bethe Bloch, Bremsstrahlung, Photo-electric effect, Compton scattering and Pair production) for charged particles and photons; introduce radiation length and EM showers
- Additional strong interactions for hadrons; hadronic absorption/interaction length and hadronic showers
- Neutrinos weakly interacting with matter

Next steps

How do we use that fact that we now know how most particles (i.e all particles that live long enough to reach a detector; e,μ,p,π,k,n,photons, neutrinos,etc) **react with matter ?**

Q: What is a detector supposed to measure ?

A1 : All important parameters of the particles produced in an experiment; p, E, v, charge, lifetime, identification, etc

With high efficiency and over the full solid angle of course.

A2 : Keeping in mind that secondary vertices and combinatorial analysis provide information about c,b-quarks, τ's, converted photons, neutrinos, etc

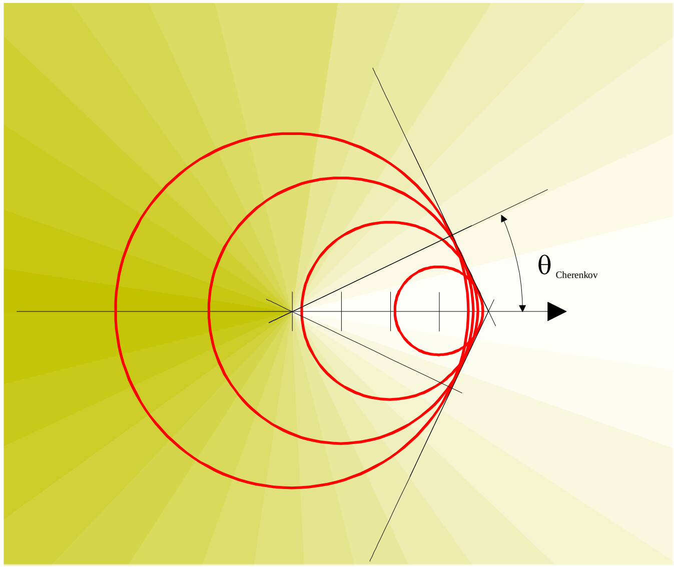
Next steps; look at some specific measurements where "special effects" or clever detector configuration is used:

- Cherenkov and Transitions radiation important in detector systems since the effects can be used for particle ID and tracking, even though energy loss is small
- This naturally leads to particle ID with various methods
  - dE/dx, Cherenkov, TRT, EM/HAD, p/E
- Look at magnetic systems and multiple scattering
- Secondary vertices and lifetime

Cherenkov

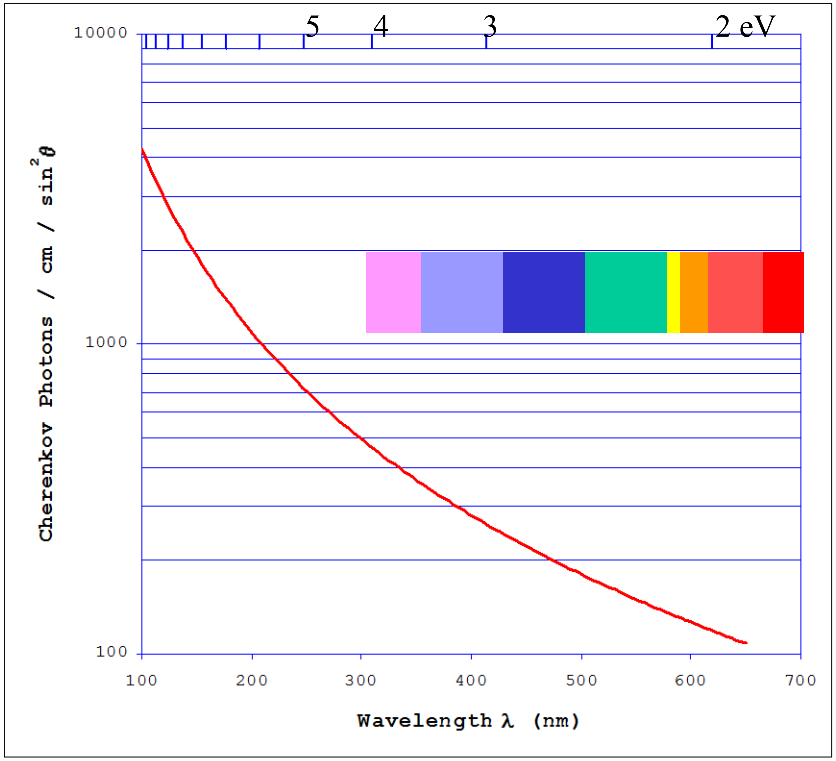
CERN-Claf, O.Ullaland

A particle with velocity β β=v/c
in a medium with refractive index *n*
may emit light along a conical wave front if the speed is greater than speed of light in this medium : c/n



The angle of emission is given by

$$\cos\theta = \frac{c/nt}{\beta ct} = \frac{1}{\beta n}$$



and the number of photons by

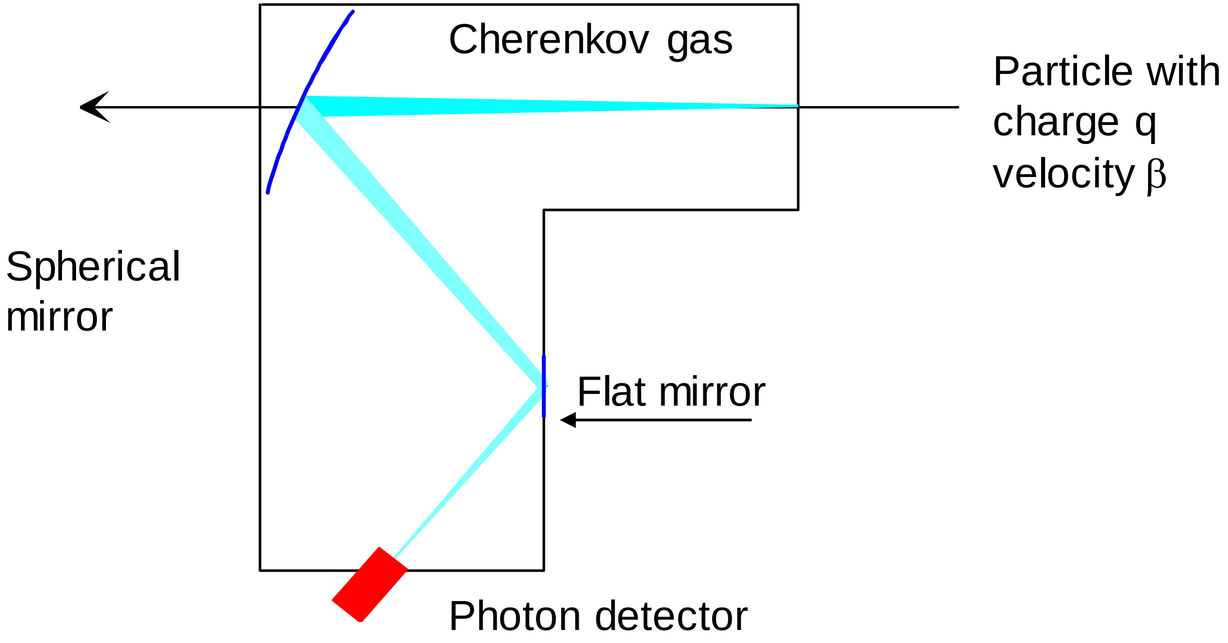
$$N[\lambda_1 \rightarrow \lambda_2] = 4.6 \cdot 10^6 \left[\tfrac{1}{\lambda_2(A)} - \tfrac{1}{\lambda_1(A)}\right] L(cm) \sin^2\theta$$

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

Cherenkov

CERN-Claf, O.Ullaland

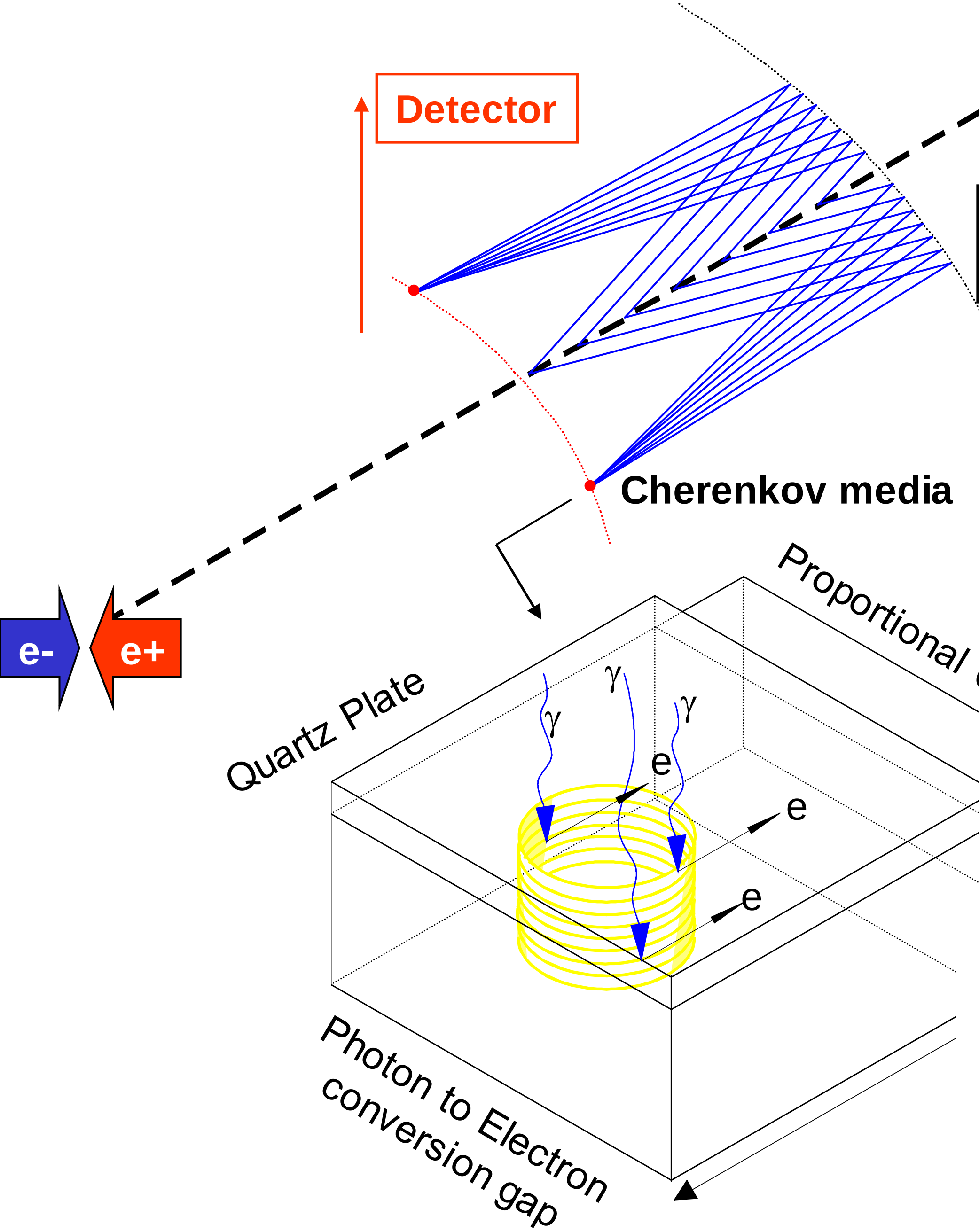
Threshold Cherenkov Counter, chose suitable medium (n)

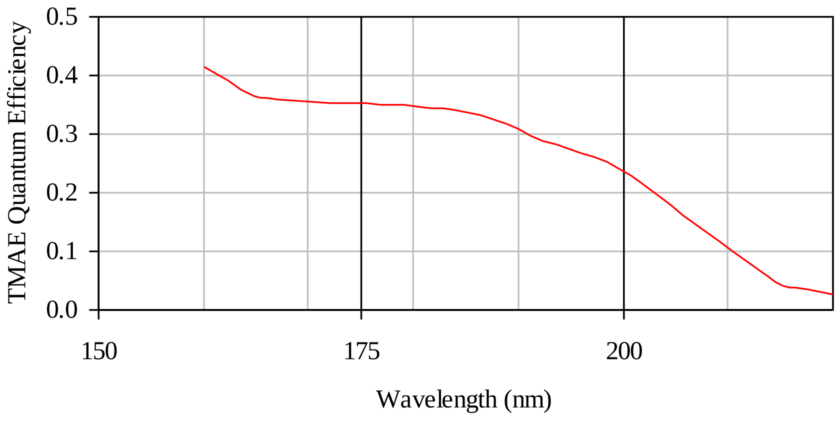


To get a better particle identification, use more than one radiator.

Cherenkov

CERN-Claf, O.Ullaland

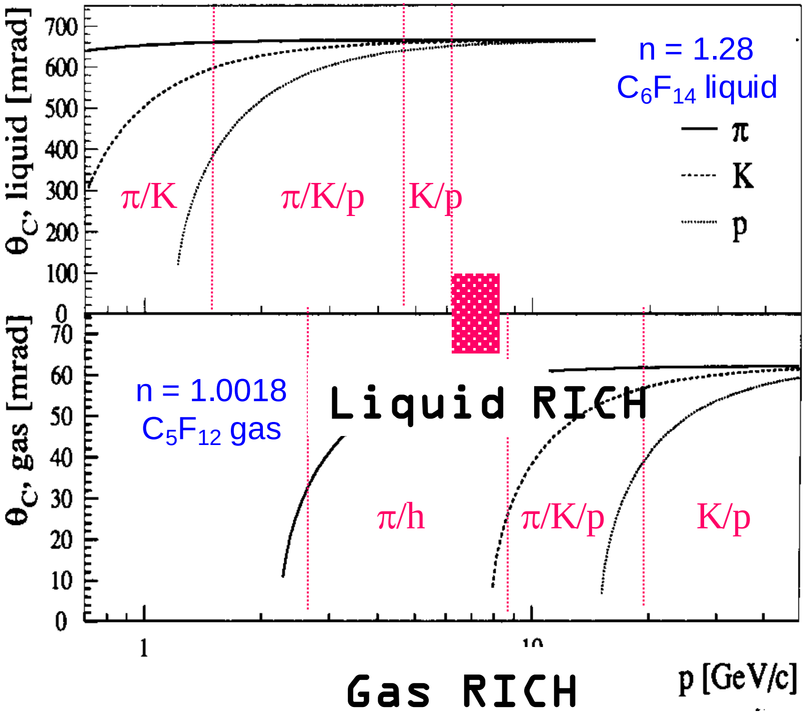




Particle Identification in DELPHI at LEP I and LEP II

→$0.7 \leq p \leq 45$ GeV/c

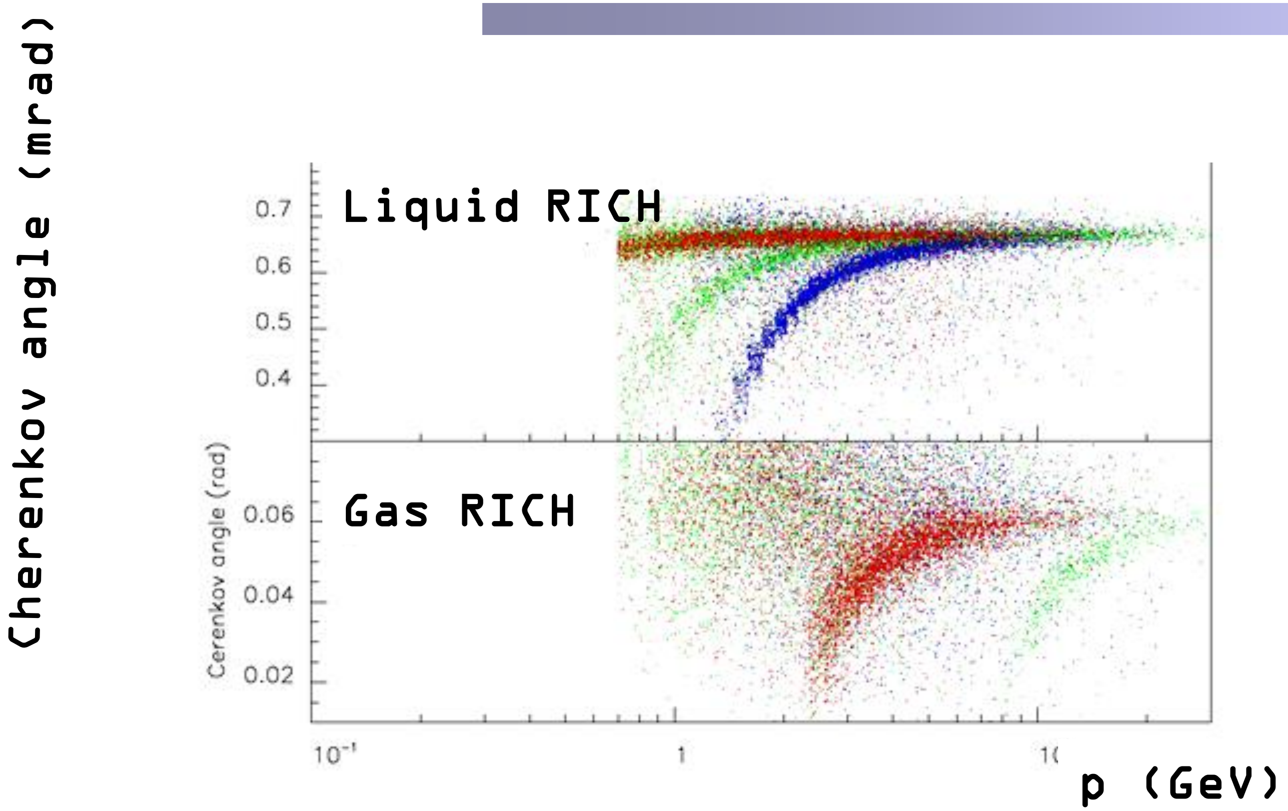
→$15° \leq \theta \leq 165°$



2 radiators + 1 photodetector

Cherenkov

CERN-Claf, O.Ullaland



From data

p from Λ **K from Φ D^*** **π from K^0**

Transition Radiation

Electromagnetic radiation is emitted when a charged particle transverses a medium with discontinuous refractive index, as the boundary between vacuum and a dielectric layer.
B.Dolgosheim (NIM A 326 (1993) 434) for details.
Energy per boundary :

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$$

Only high energy e+- will emit TR, electron ID.

$$\hbar\omega_p = \hbar\sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \approx 20eV$$

Plastic radiators

An exact calculation of **Transition Radiation** is complicated (`J. D. Jackson)` and he continues:

A charged particle in uniform motion in a straight line in free space does not radiate

A charged particle moving with constant velocity can radiate if it is in a material medium and is moving with a velocity greater than the phase velocity of light in that medium (Cherenkov radiation)

There is another type of radiation, transition radiation, that is emitted when a charged particle passes suddenly from one medium to another.

Transition Radiation

The number of photons are small so many transitions are needed; use a stack of radiation layers interleaved by active detector parts.

$$W / \hbar\omega_p\gamma \propto \alpha$$

The keV range photons are emitted at a small angle.

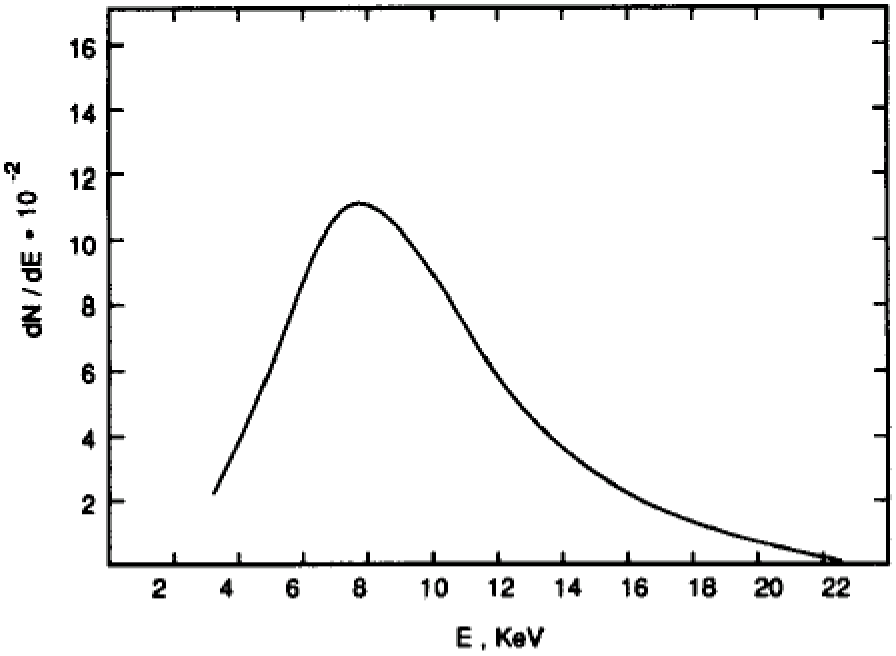
$$\hbar\omega_p\gamma, \theta \propto 1/\gamma$$

The radiation stacks has to be transparent to these photons (low Z); hydrocarbon foam and fibre materials.

The detectors have to be sensitive to the photons (so high Z, for example Xe (Z=54)) and at the same time be able to measure dE/dx of the "normal" particles which has significantly lower energy deposition.

- Simulated emission spectrum of a CH_2 foil stack

From C.Joram



Transition Radiation

ATLAS **Transition** **Radiation** **Tracker**

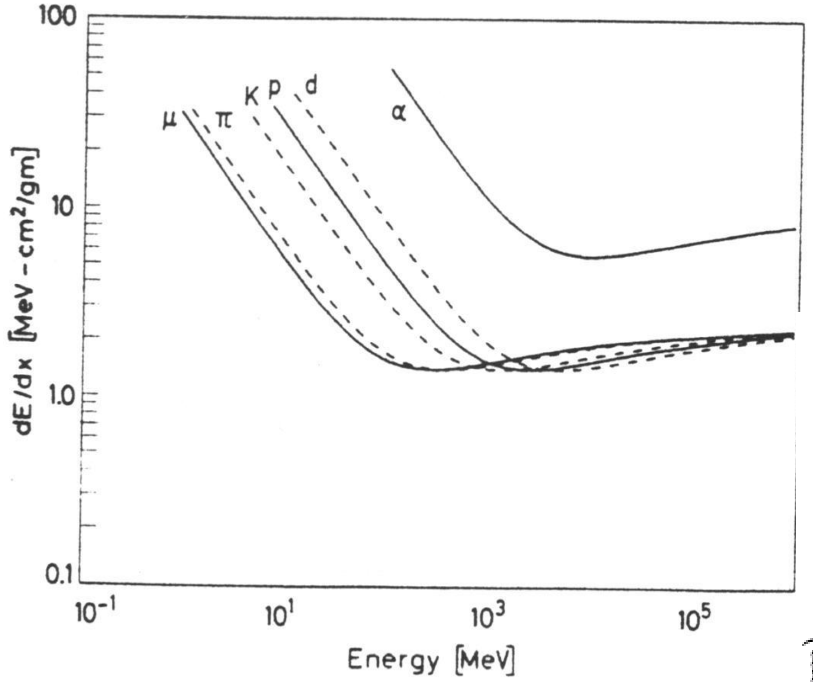
A prototype endcap “wheel”.

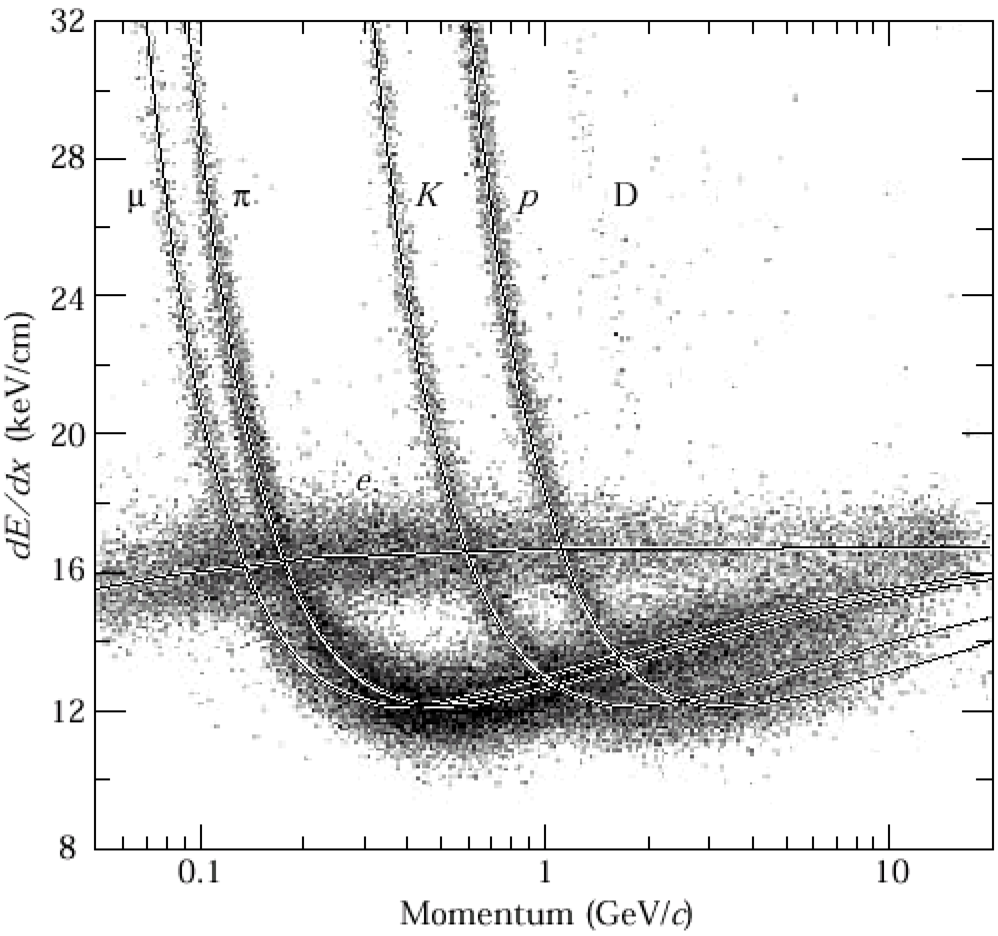
X-ray detector: straw tubes (4mm) (in total ca. 400.000 !)

Xe based gas

Around 600 TR layers are used in the stacks … 15 in between every active layer

dE/dx



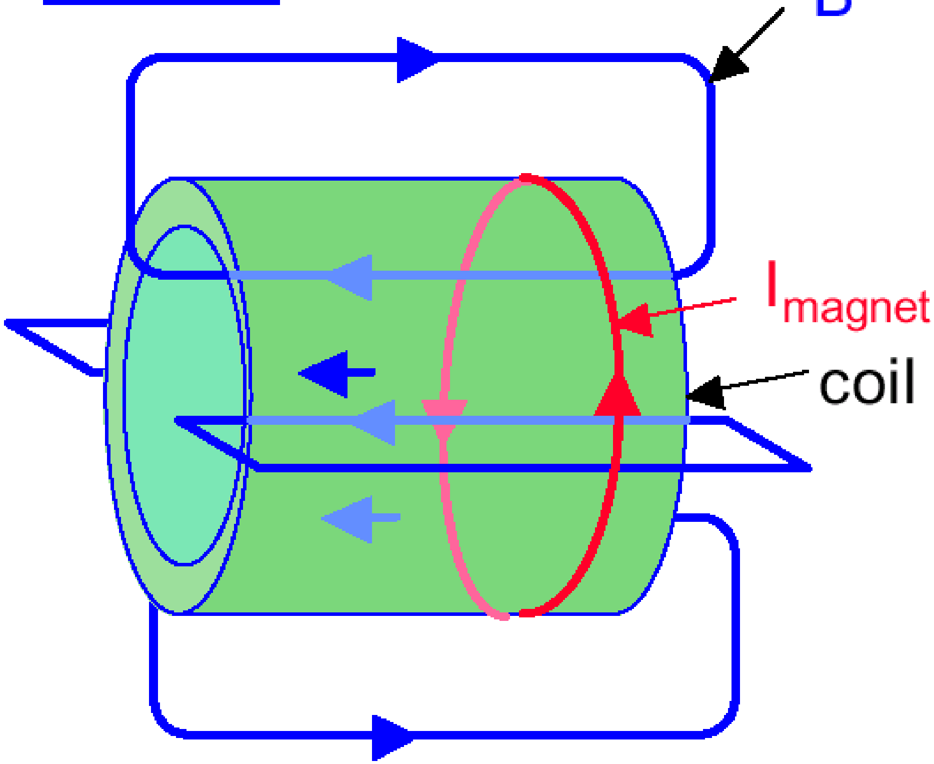


dE/dx can be used to identify particles at relatively low momentum. The figure above is what one would expect from Bethe Bloch, on the left data from the PEP4 TPC with 185 samples (many samples important).

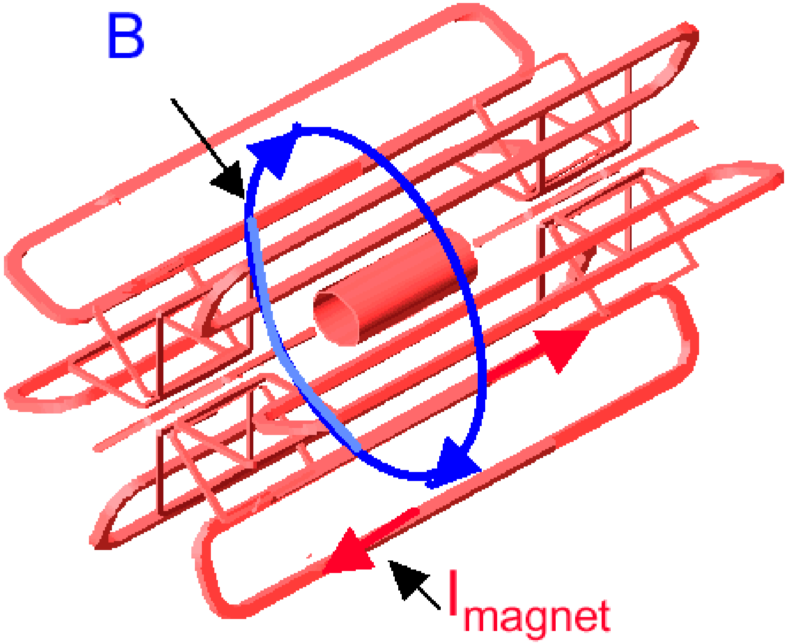
Magnetic fields

Magnetic field configurations:

solenoid



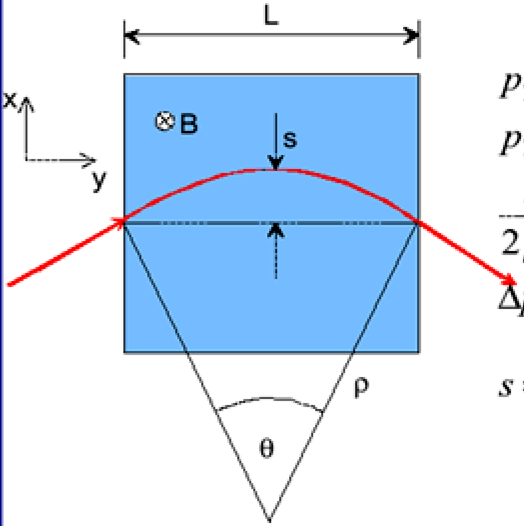
toroid



From C.Joram

See the Particle Data Book for a discussion of magnets, stored energy, fields and costs.

Momentum measurement



$$p_T = qB\rho$$

$$p_T\,(\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T\cdot m})$$

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

$$\Delta p_T = p_T\sin\theta \approx 0.3L\cdot B$$

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

the sagitta s is determined by 3 measurements with error $\sigma(x)$: $s = x_2 - \frac{x_1+x_3}{2}$

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(s)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)}{s} = \frac{\sqrt{\frac{3}{2}}\sigma(x)\cdot 8p_T}{0.3\cdot BL^2}$$

for N equidistant measurements, one obtains

(R.L. Gluckstern, NIM 24 (1963) 381)

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} = \frac{\sigma(x)\cdot p_T}{0.3\cdot BL^2}\sqrt{720/(N+4)} \qquad \text{(for } N \geq\approx 10\text{)}$$

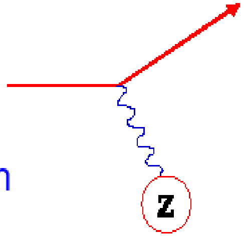
ex: p_T=1 GeV/c, L=1m, B=1T, $\sigma(x)$=200µm, N=10

$$\left.\frac{\sigma(p_T)}{p_T}\right|^{meas.} \approx 0.5\% \qquad (s \approx 3.75\ \mathrm{cm})$$

From C.Joram

Multiple scattering

Scattering

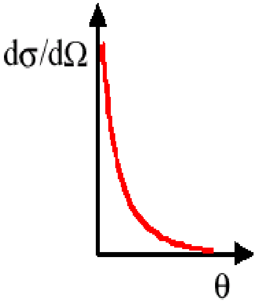


An incoming particle with charge z interacts with a target of nuclear charge Z. The cross-section for this e.m. process is

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

Rutherford formula

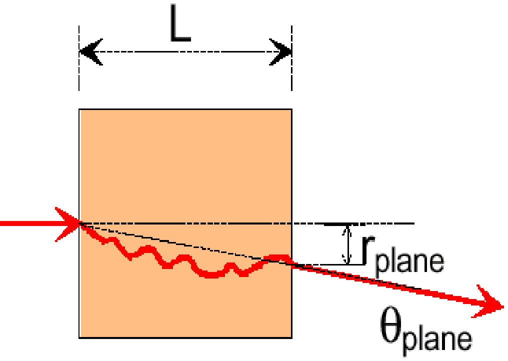
- Average scattering angle $\langle\theta\rangle = 0$

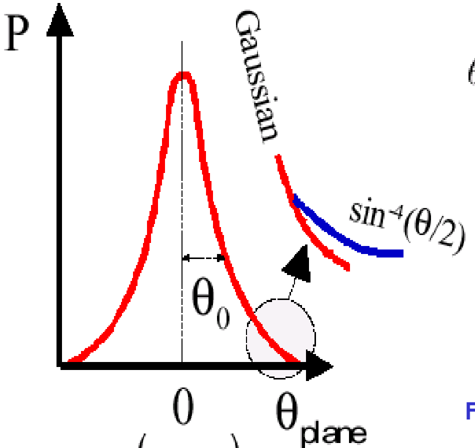


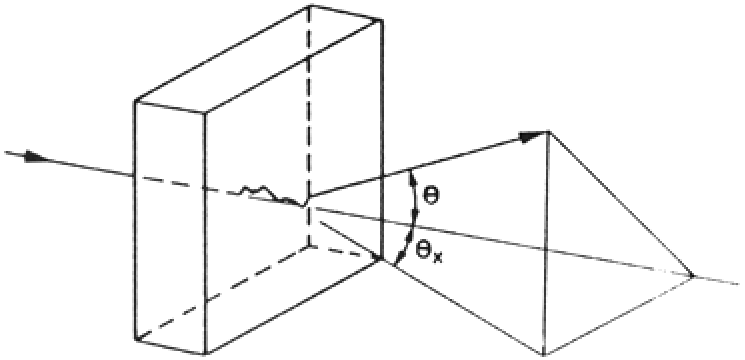
Multiple Scattering

Sufficiently thick material layer

→ the particle will undergo multiple scattering.







Usually a Gaussian approximation is used with a width expressed in terms of radiation lengths (good to 11% or better) :

$$\theta_0 = \theta_{\rm plane}^{\rm rms} = \frac{1}{\sqrt{2}}\theta_{\rm space}^{\rm rms} .$$

$$\theta_0 = \frac{13.6\ {\rm MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big] .$$

From C.Joram

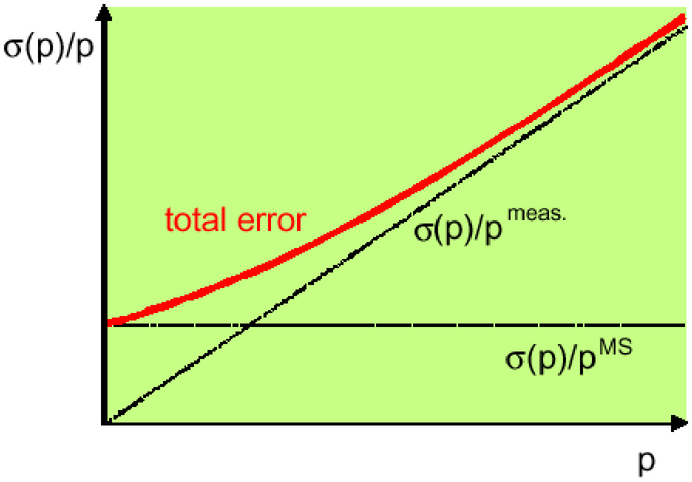
Magnetic fields

Multiple Scattering will Influence the measurement (see previous slide for the scattering angle θ) :

$$\Delta p^{MS} = p\sin\theta_0 \approx p\cdot 0.0136\frac{1}{p}\sqrt{\frac{L}{X_0}}$$

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = \frac{\Delta p^{MS}}{\Delta p_T} = \frac{0.0136\sqrt{\frac{L}{X_0}}}{0.3BL} = 0.045\frac{1}{B\sqrt{LX_0}}$$

independent of p !



ex: Ar (X_0=110m), L=1m, B=1T $\left.\frac{\sigma(p)}{p_T}\right|^{MS} \approx 0.5\%$

From C.Joram

Vertexing and secondary vertices

This is obviously a subject for a talk on its own so let me summarize in 5 lines : Several important measurements depend on the ability to tag and reconstruct particles coming from secondary vertices hundreds of microns from the primary (giving track impact parameters in the tens of micron range), to identify systems containing b,c,τ's; i.e generally systems with these types of decay lengths.

This is naturally done with precise vertex detectors where three features are important :

- Robust tracking close to vertex area
- The innermost layer as close as possible
- Minimum material before first measurement in particular to minimise the multiple scattering (beam pipe most critical).

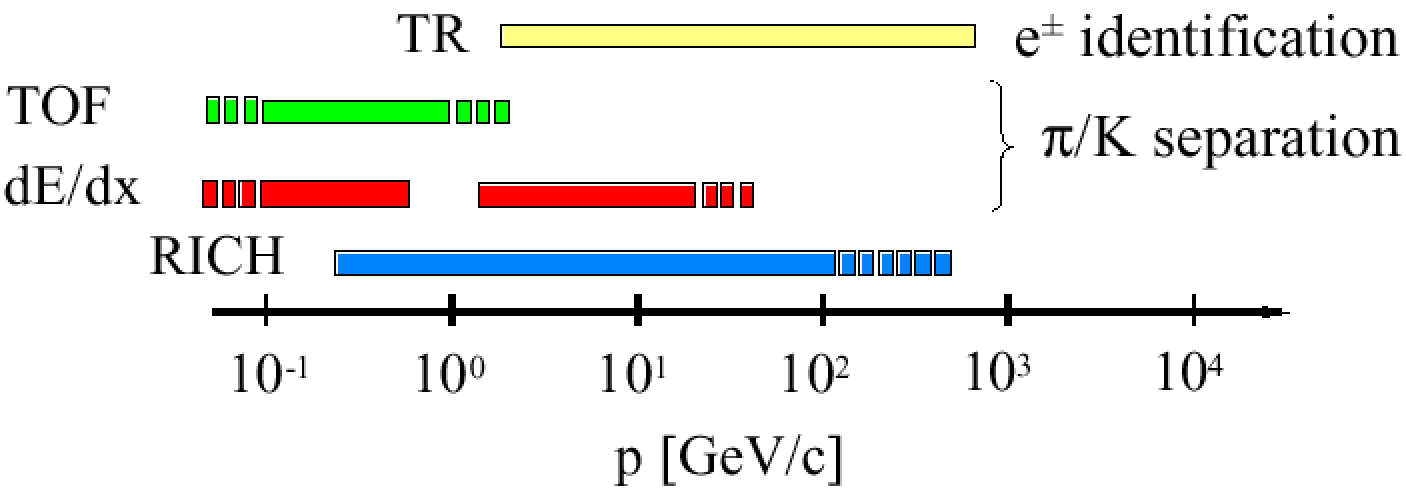
The vertex resolution of is therefore usually parametrised with a constant term (geometrical) and a term depending on 1/p (multiple scattering) and also θ (the angle to the beam-axis).

Secondary x

Primary x

Summary

A very coarse plot ….



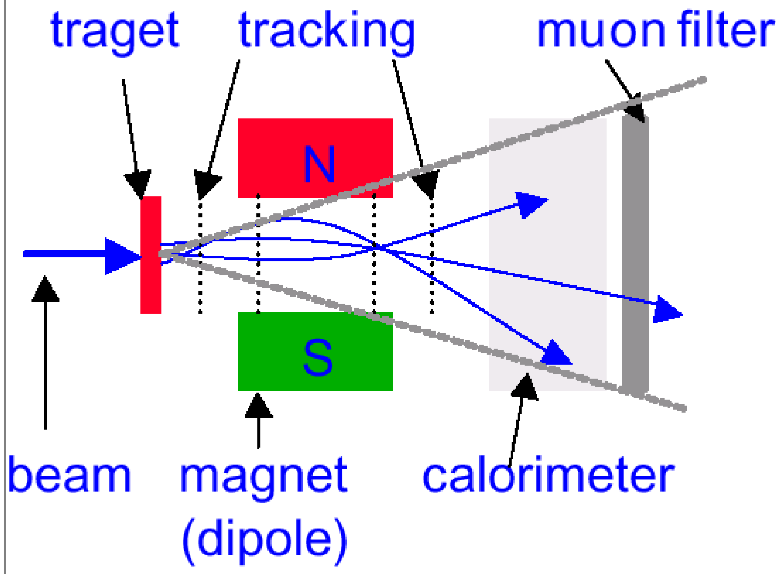
In addition we should keep in mind that EM/HAD energy deposition provide particle ID, matching of p (momentum) and EM energy the same (electron ID), isolation cuts help to find leptons, vertexing help us to tag b,c or τ, missing transverse energy indicate a neutrino, etc so a number of methods are finally used in experiments.

Detector systems

Geometrical concepts

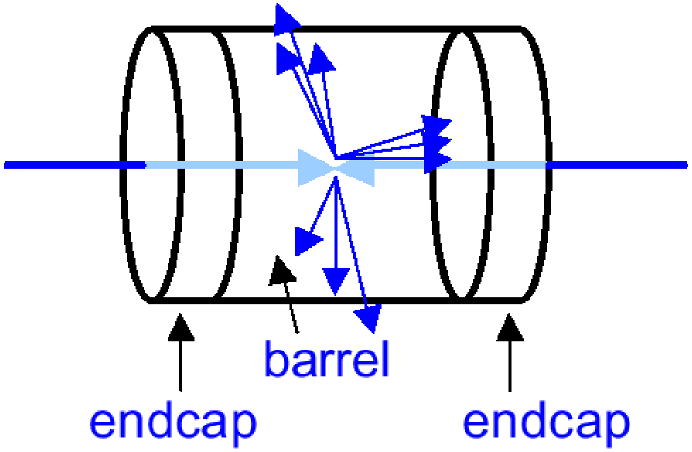
Fix target geometry

"Magnet spectrometer"



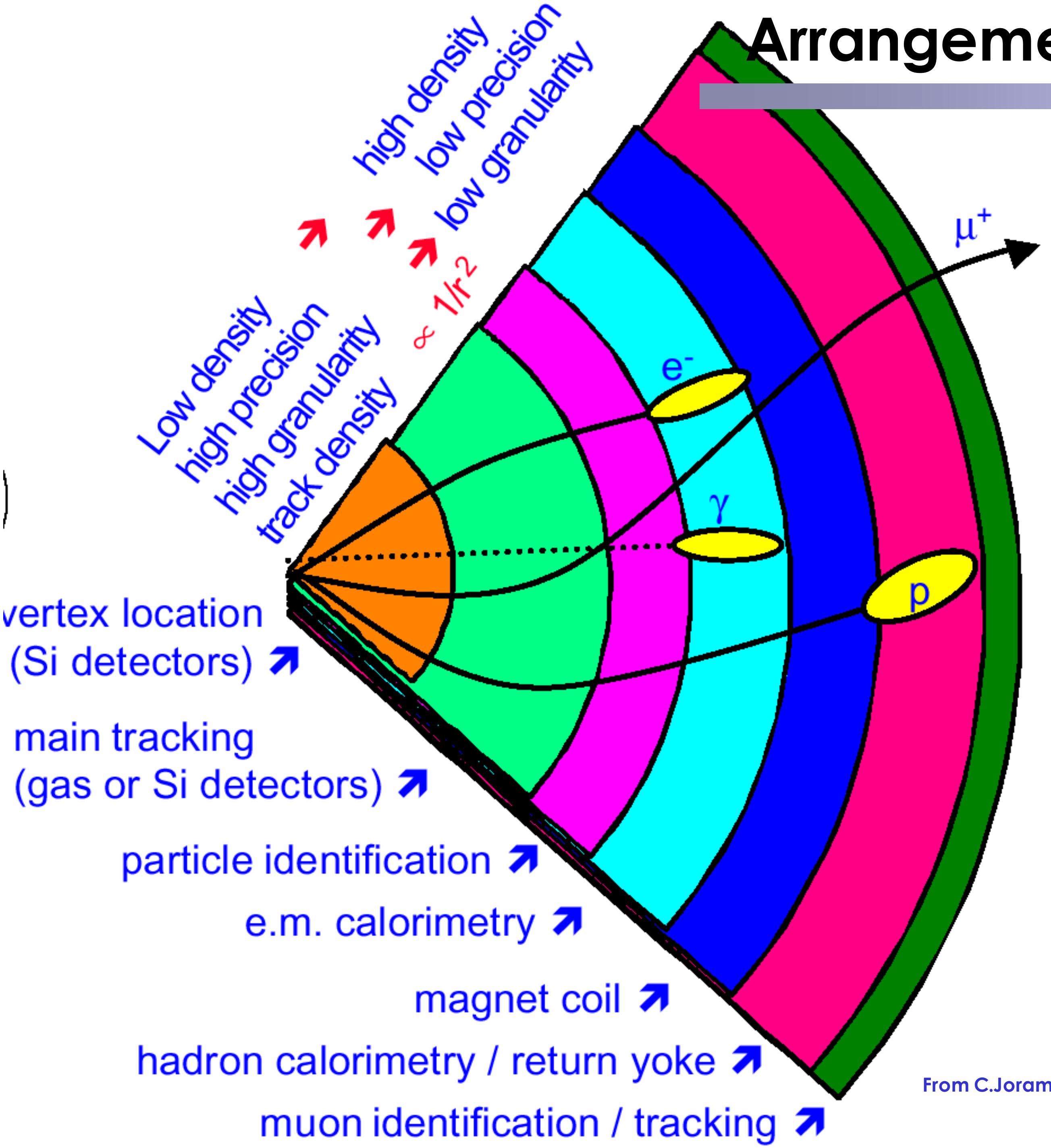
Collider Geometry

"4π Multi purpose detector"



From C.Joram

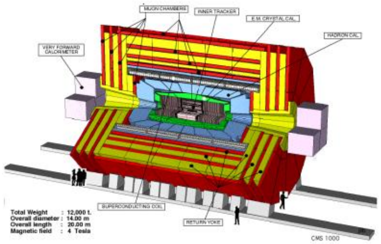
Arrangement of detectors

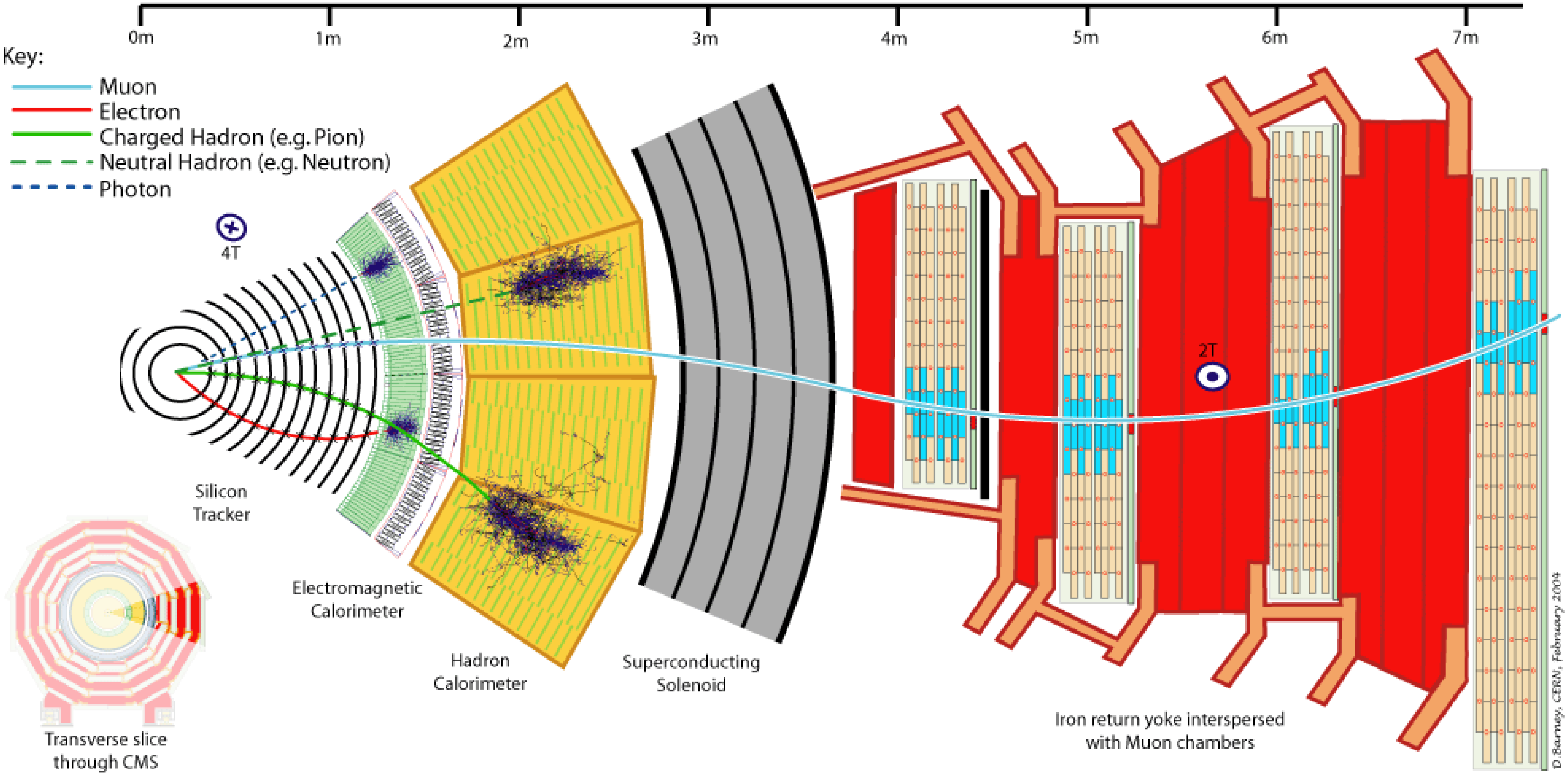


From C.Joram

We see that various detectors and combination of information can provide particle identification; for example p versus EM energy for electrons; EM/HAD provide additional information, so does muon detectors, EM response without tracks indicate a photon; secondary vertices identify b,c, τ's; isolation cuts help to identify leptons

Particle Physics Detector

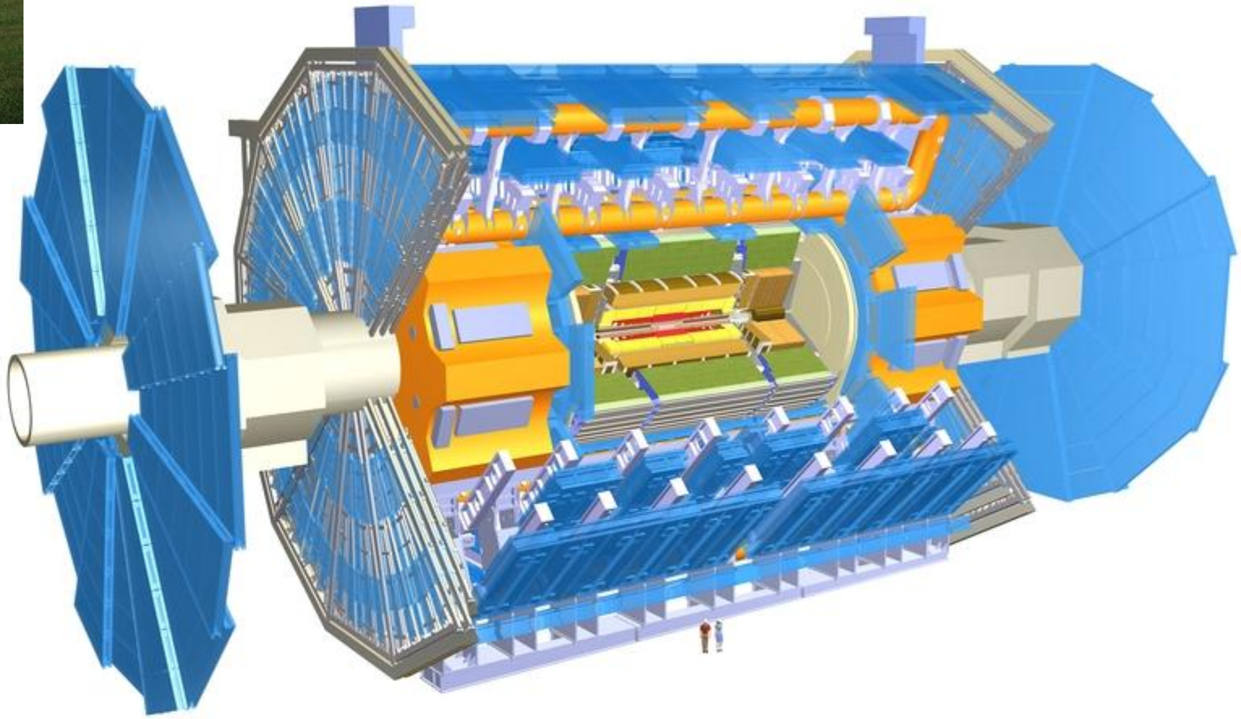




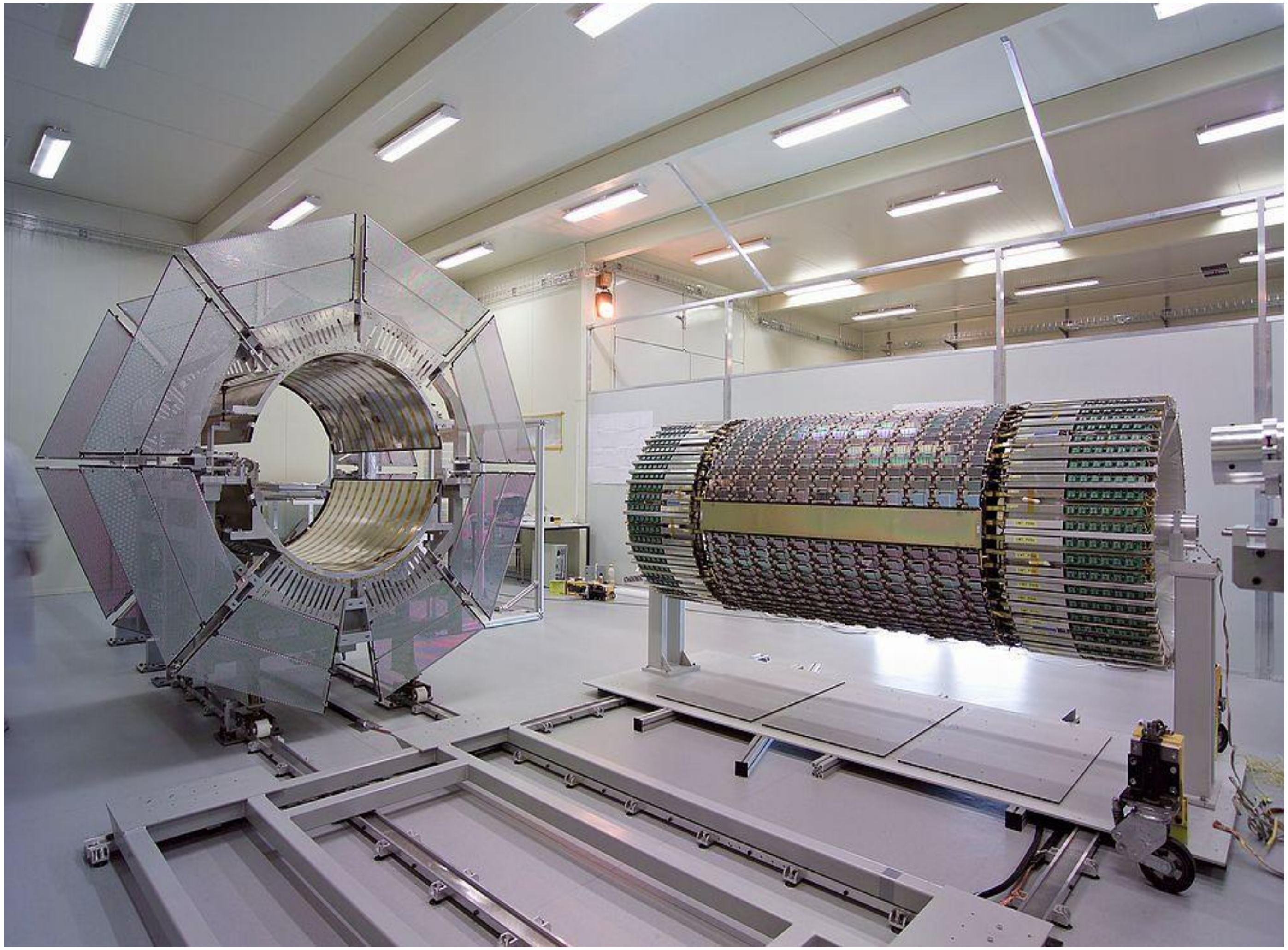
> 100 Million Electronics Channels, 40 MHz ---> TRIGGER

ATLAS superimposed to
the 5 floors of building 40

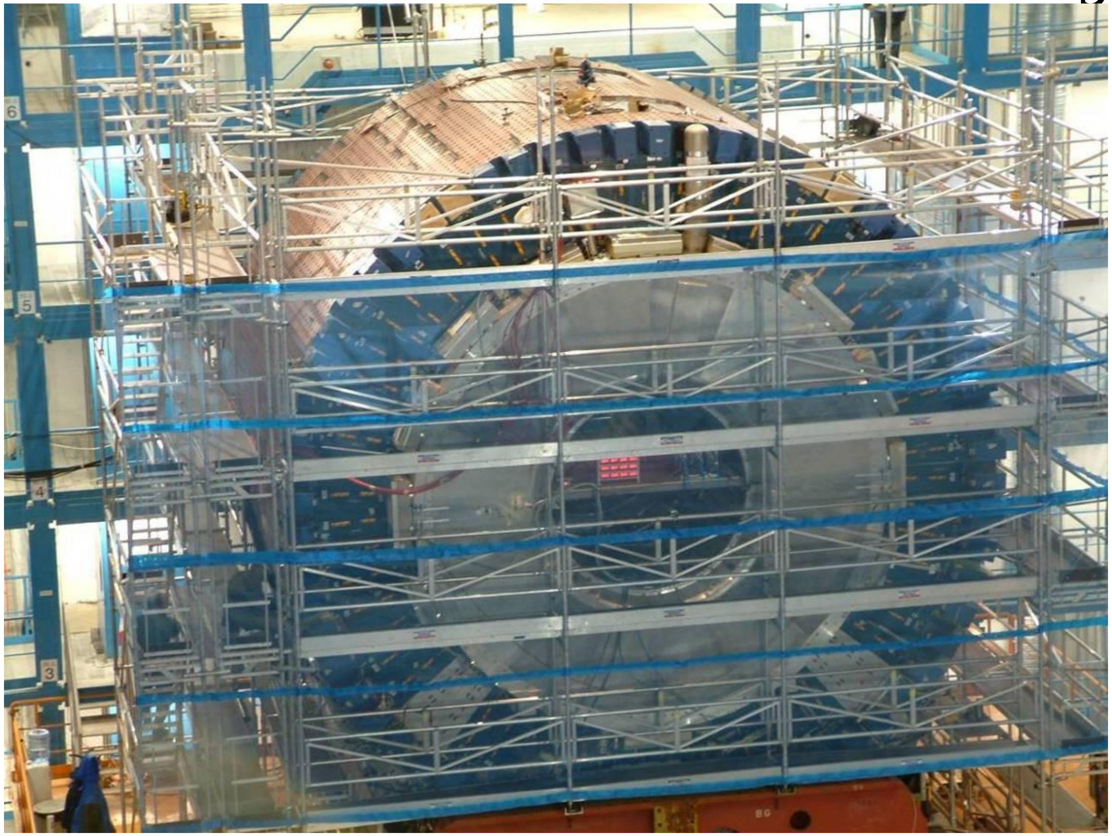
The ATLAS Detector

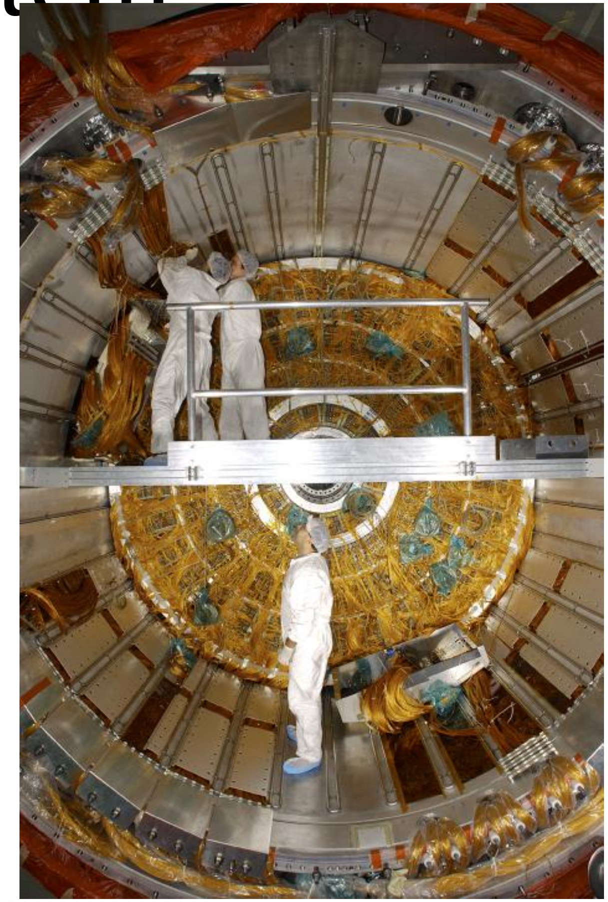


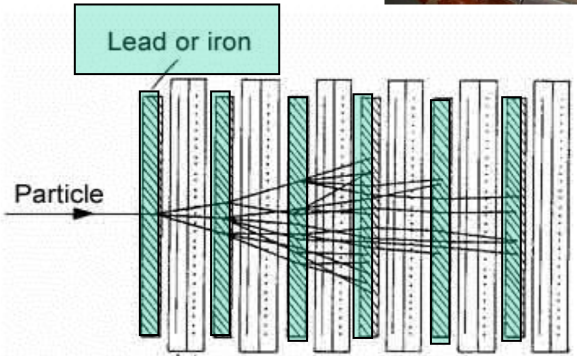
Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*



Calorimeter system








ATLAS
ONE