Instrumentation

Content

Introduction

Part 1: Passage of particles through matter

- Charges particles, Photons, Neutrons, Neutrinos
- Momentum measurements, Combining measurements.

Part 2: Particle Detection

- Ionisation detector
- Scintillation detectors
- Semiconductor detectors

Instrumentation

Experimental Particle Physics

Accelerators

- Luminosity, energy, quantum numbers

Detectors

- Efficiency, speed, granularity, resolution

Trigger/DAQ

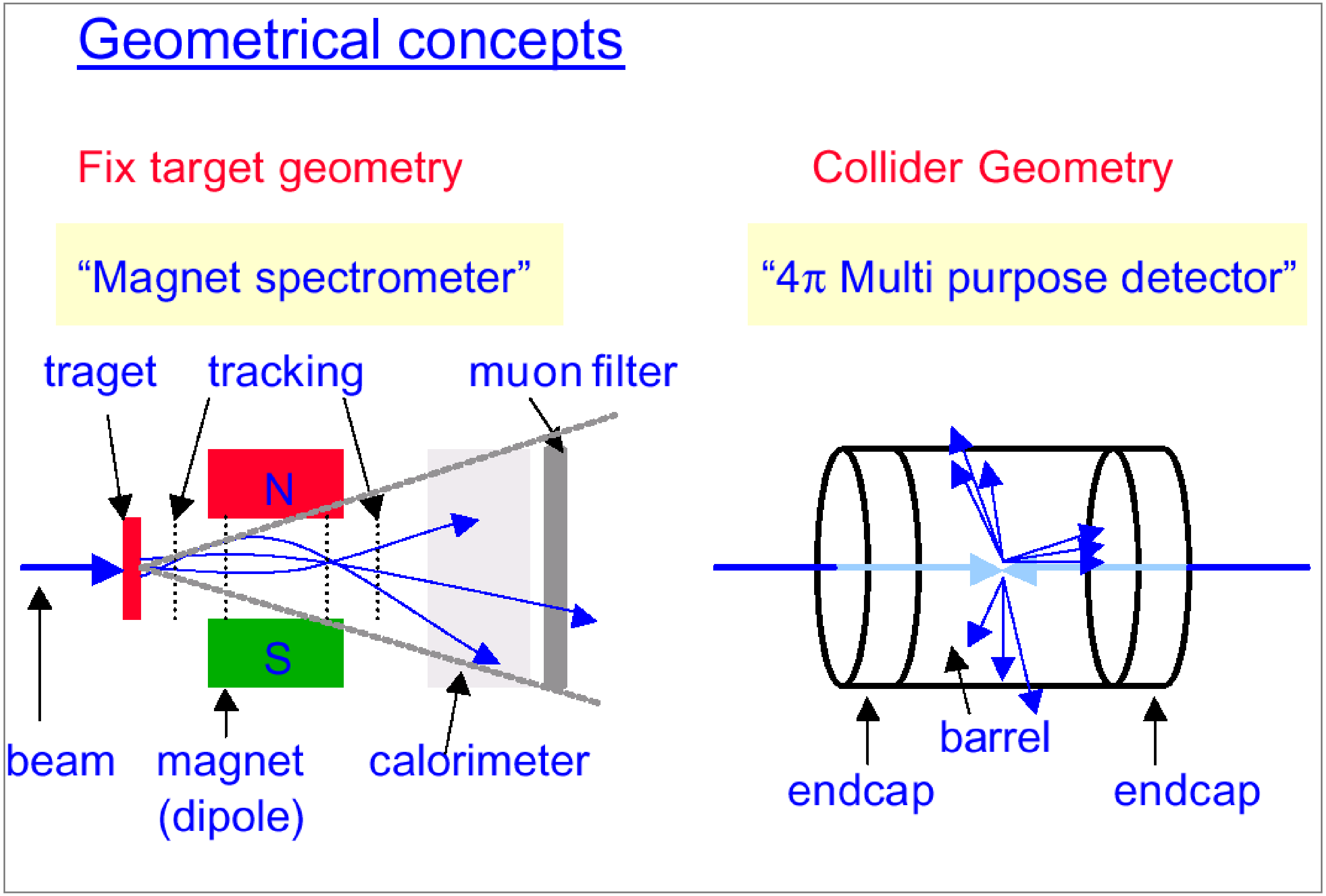
- Efficiency, compression, through-put, physics models

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.

Detector systems



Geometrical concepts

Fix target geometry

"Magnet spectrometer"

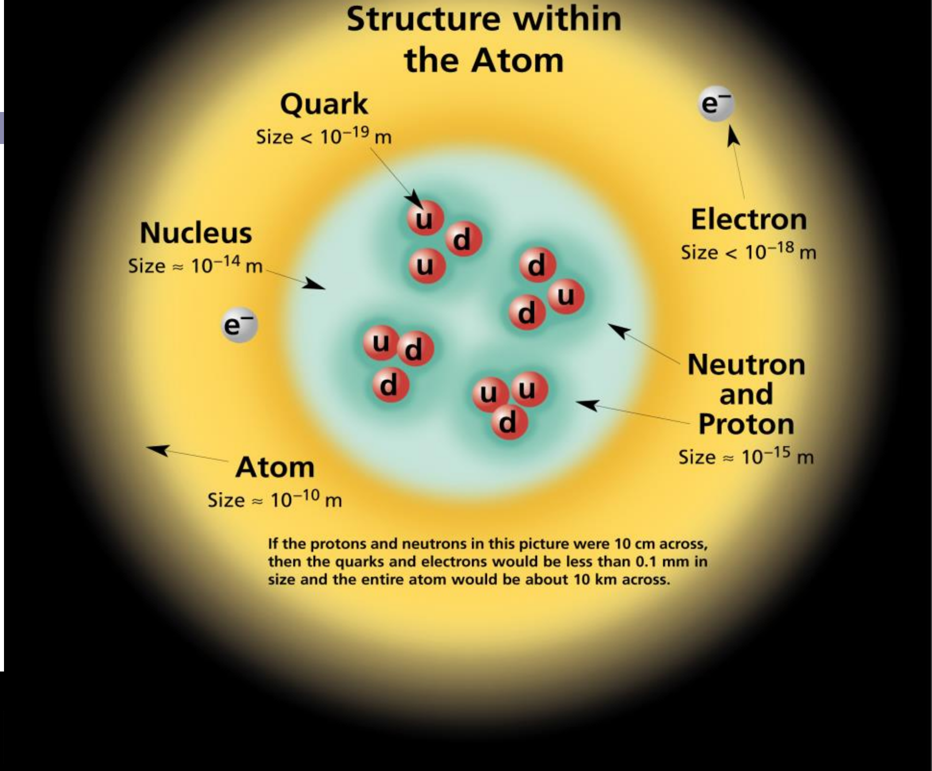
Collider Geometry

"4π Multi purpose detector"

From C.Joram

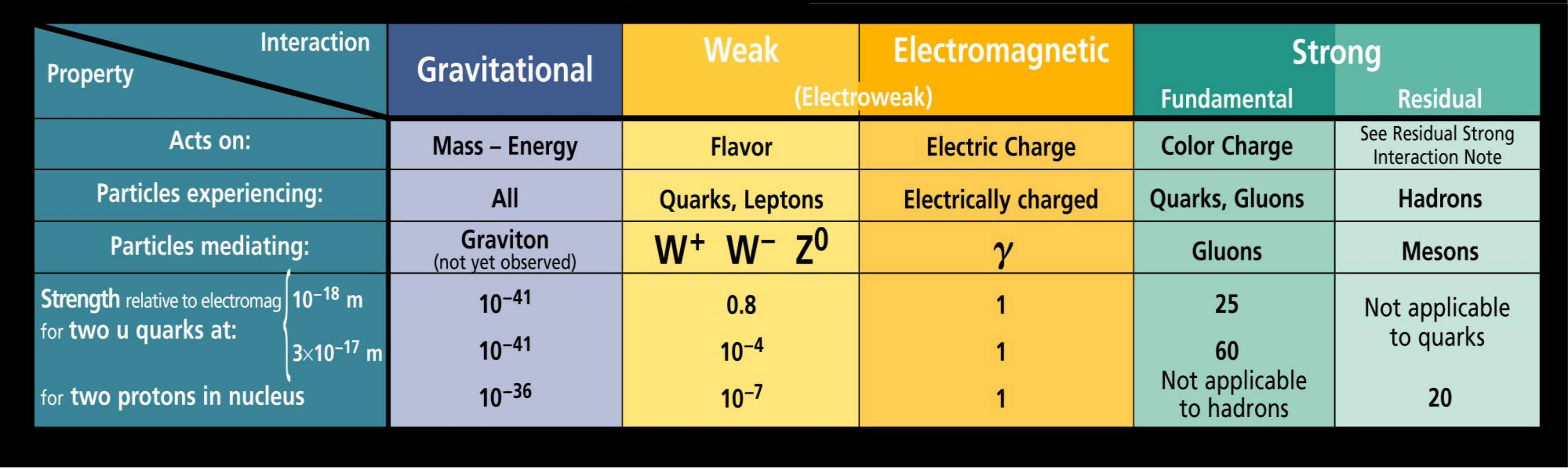
Concentrate on electromagnetic forces since a combination of their strength and reach make them the primary responsible for energy loss in matter.

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


Structure within the Atom

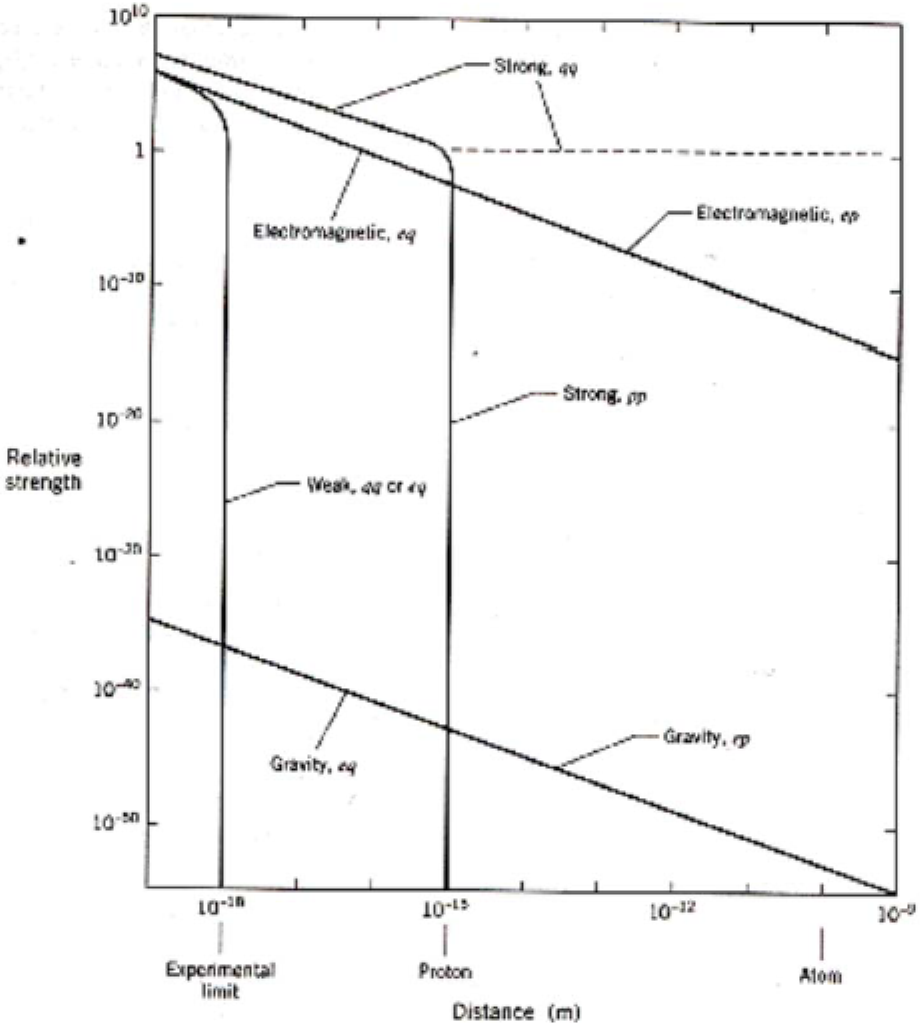
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

PROPERTIES OF TH



Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: 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

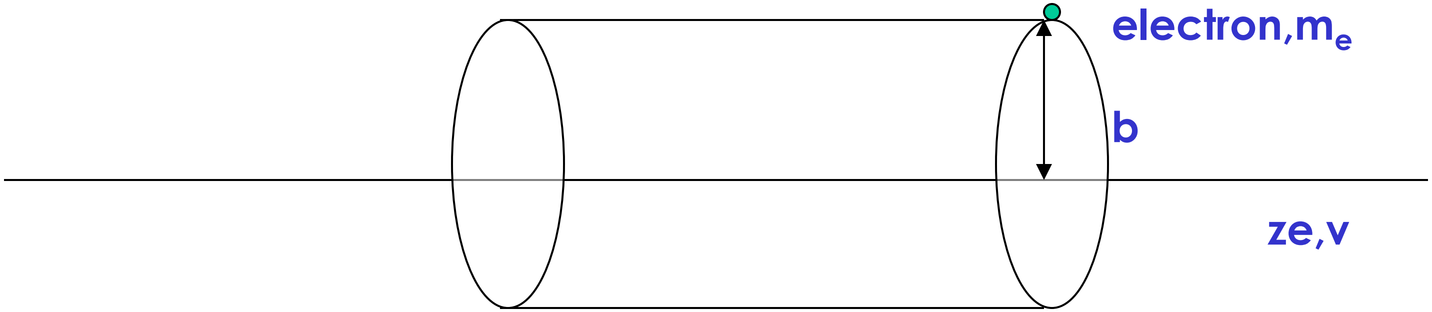
Heavy charged particles transfer energy mostly to the atomic electrons, ionising them. We will later come back to not so heavy particles, in particular electrons/positrons.

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 :

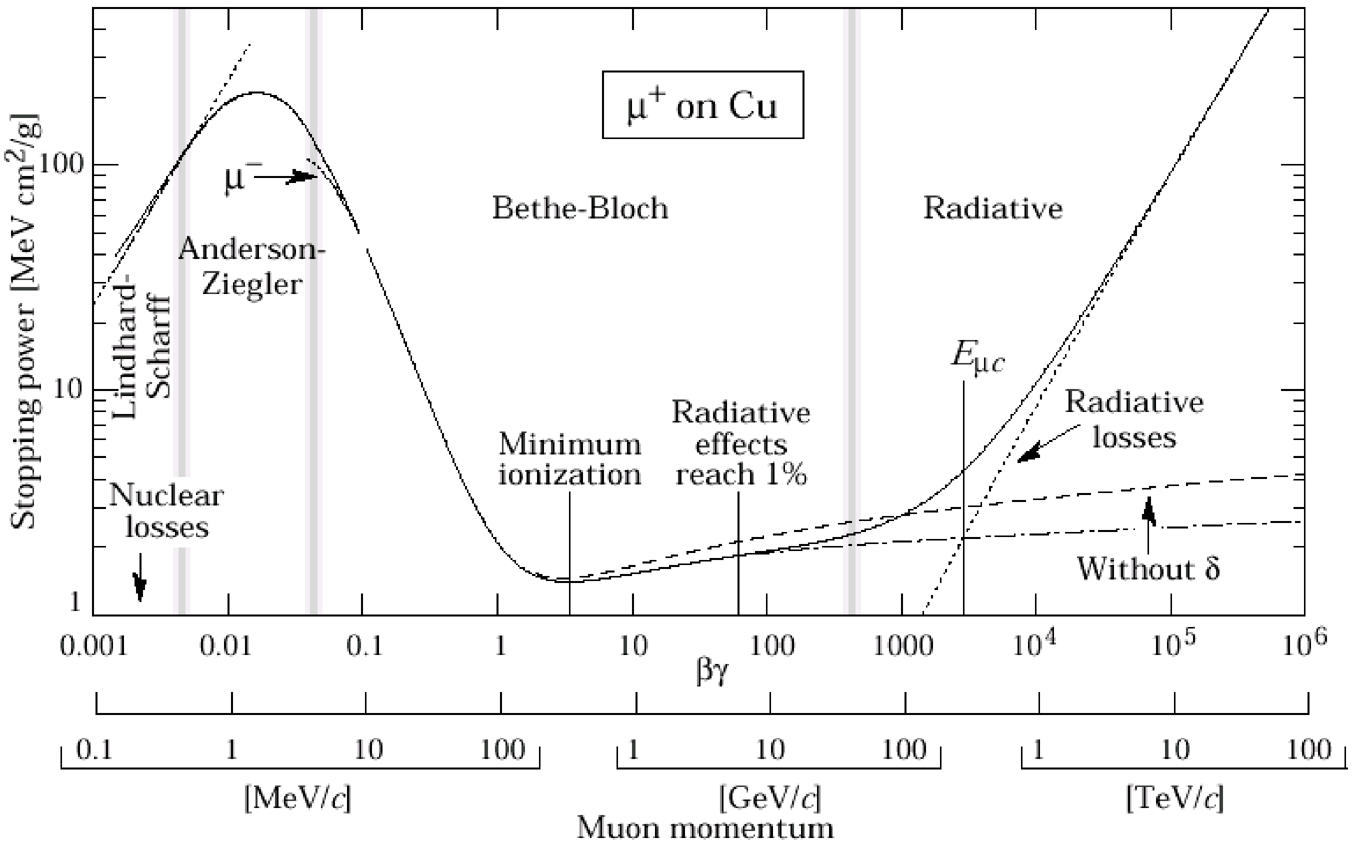
1) Let us look at energy transfer to a single electron from heavy charged particle passing at a distance b

2) Let us multiply with the number of electrons passed

3) Let us integrate over all reasonable distances b



Heavy charges particles

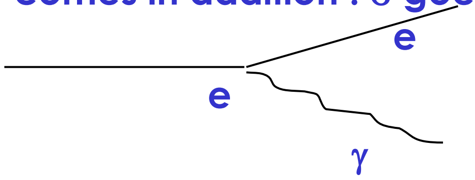


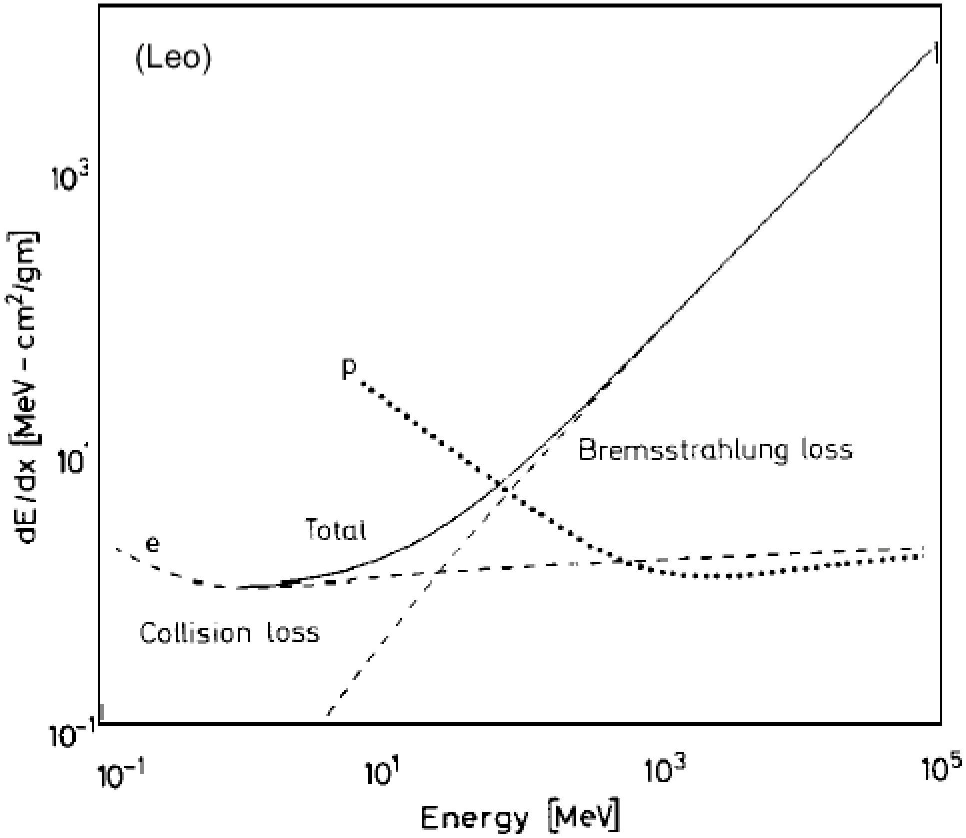
$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

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 $1/m^2$





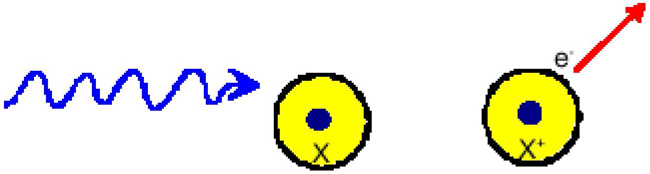
Photons

Three processes :

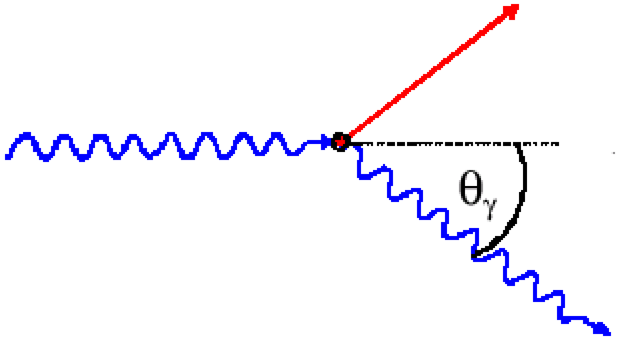
Photoelectric effect (Z^5); absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.

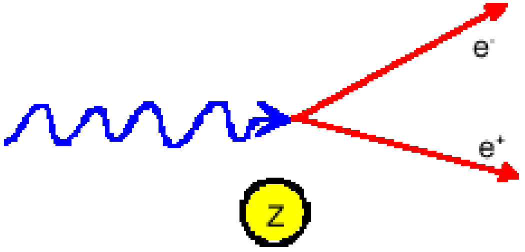
Compton scattering (Z); scattering of a photon again a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc) and for energies above a few MeV 90% of the energy is transferred (in most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



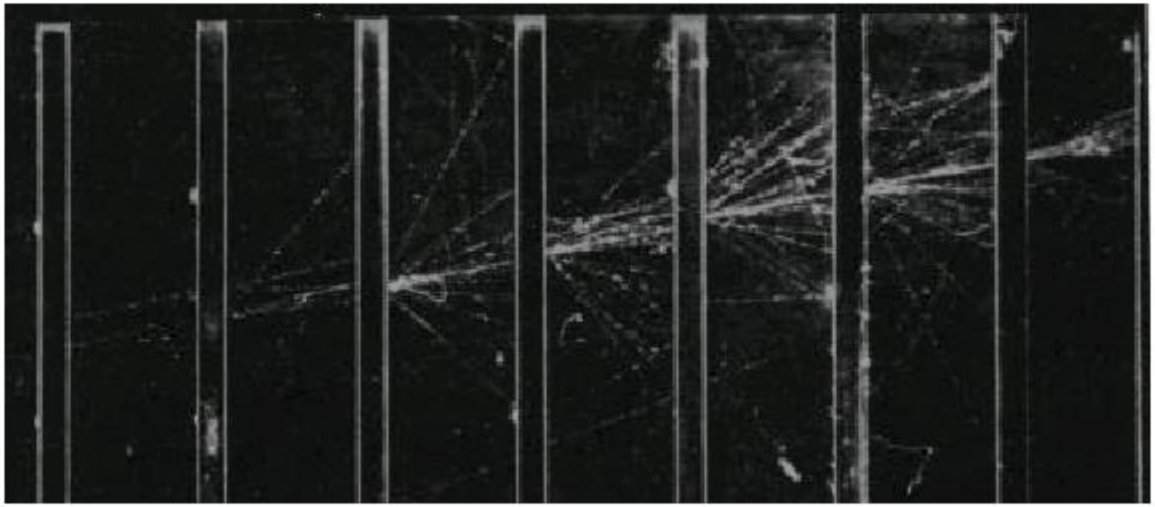
$$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$$





Plots from C.Joram

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.

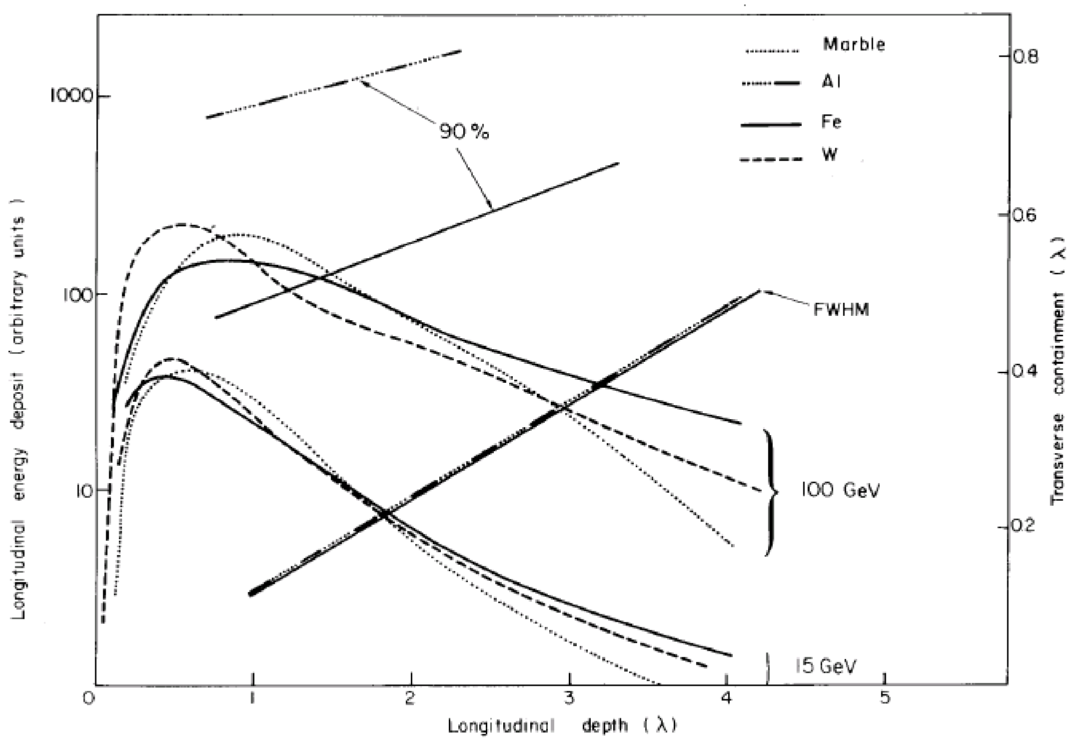
Longitudinal shower development

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)

- **Additional strong interactions for hadrons (p,n, etc) ; hadronic absorption/interaction length and hadronic showers**

Neutrinos

Neutrinos interact only weakly ⟶ tiny cross-sections

For their detection we need again first a charged particle.

Possible detection reactions:

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

The cross-section for the reaction $\nu_e + n \rightarrow e^- + p$ is of the order of 10^{-43} cm² (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: $\varepsilon_{\det} \approx 5 \cdot 10^{-17}$

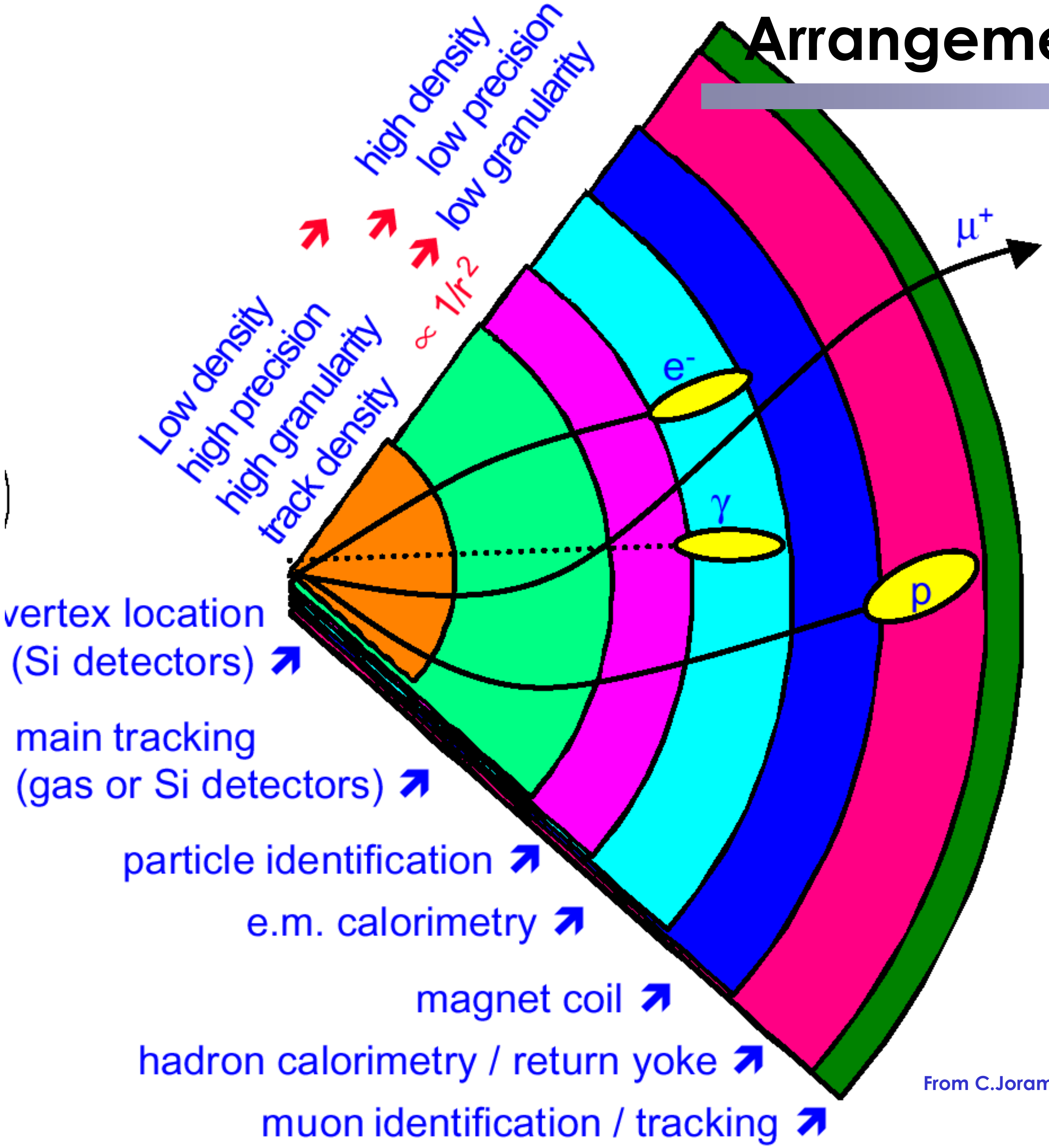
Neutrino detection requires big and massive detectors (ktons) and high neutrino fluxes.

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

Arrangement of detectors



Low density
high precision
high granularity
track density

∝ $1/r^2$

high density
low precision
low granularity

vertex location (Si detectors) ↗

main tracking (gas or Si detectors) ↗

particle identification ↗

e.m. calorimetry ↗

magnet coil ↗

hadron calorimetry / return yoke ↗

muon identification / tracking ↗

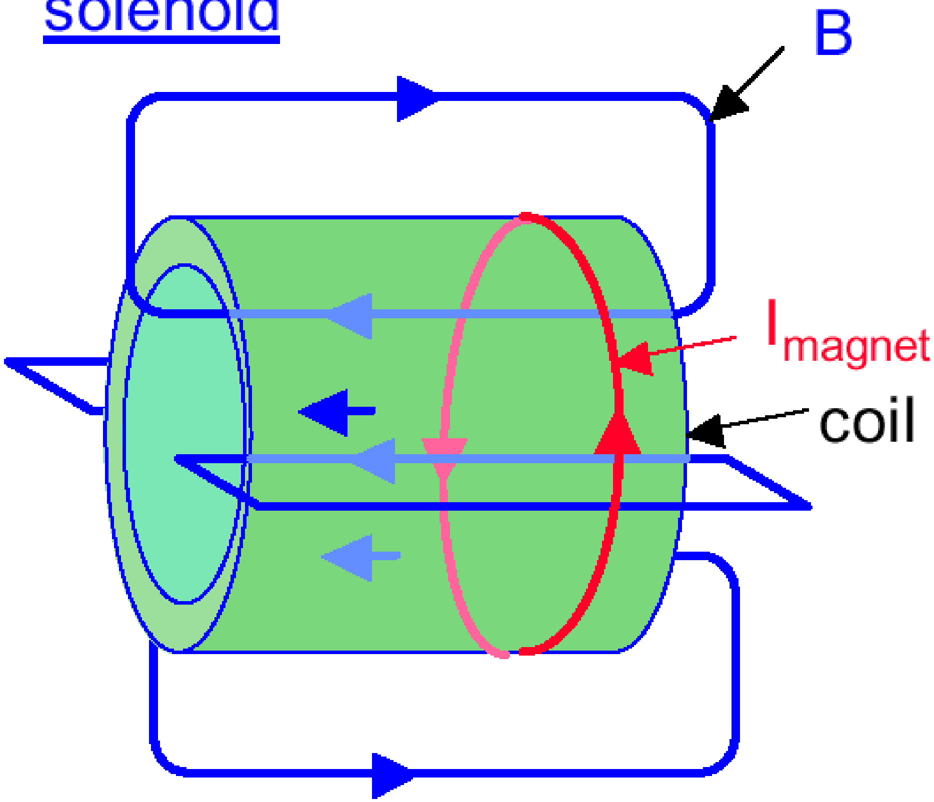
From C.Joram

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

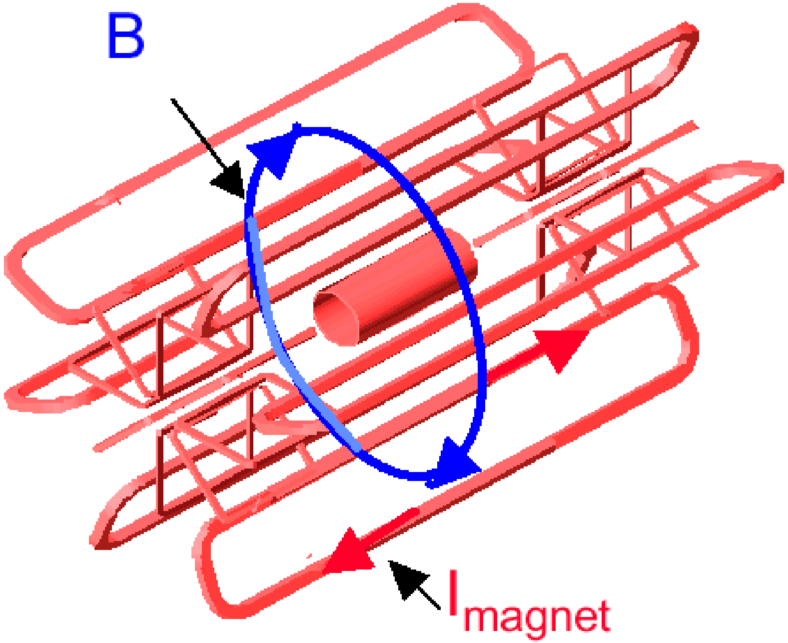
Magnetic fields

Magnetic field configurations:

solenoid



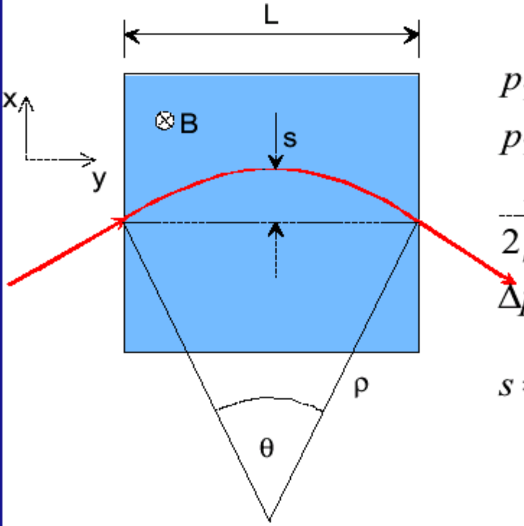
toroid



From C.Joram

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

Momentum measurement



$$p_T = qB\rho$$

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

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

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

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

the sagitta s is determined by 3 measurements with error *σ(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)

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

ex: p_T=1 GeV/c, L=1m, B=1T, σ(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

Instrumentation

Lecture set 2 : How are reactions of the various particles with detectors turned into electrical signals. We would like to extract position and energy information channel by channel from our detectors.

Three effects are usually used :

1 Ionisation

2 Scintillation

3 Semi Conductors

and these are used in either for tracking, energy measurements, photon detectors for Cherenkov or TRT, etc

and from then on it is all online (trigger, DAQ) and offline treatment and analysis ....

Ionisation Detectors

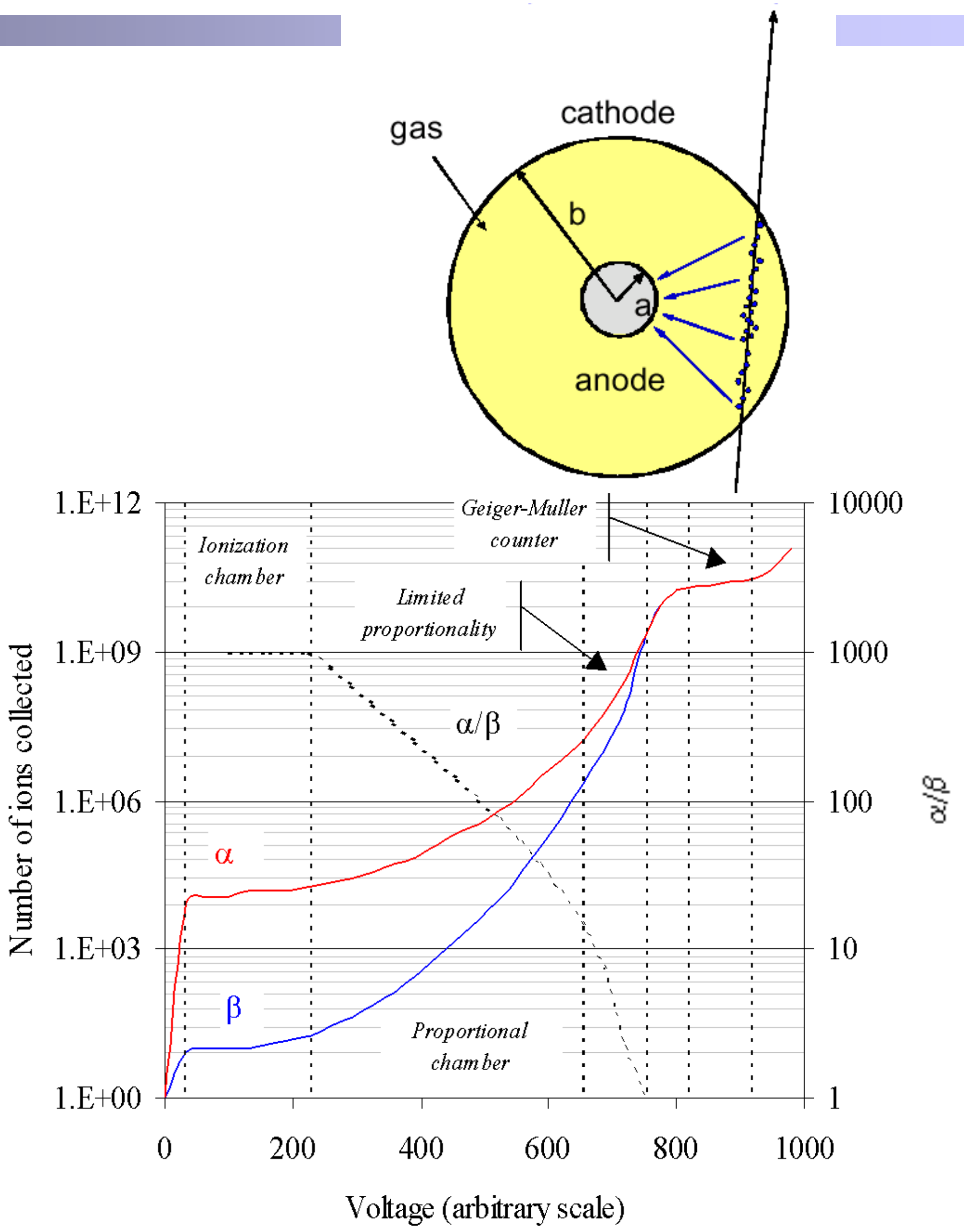
The different regions :

Recombination before collection.

Ionisation chamber; collect all primary charge. Flat area.

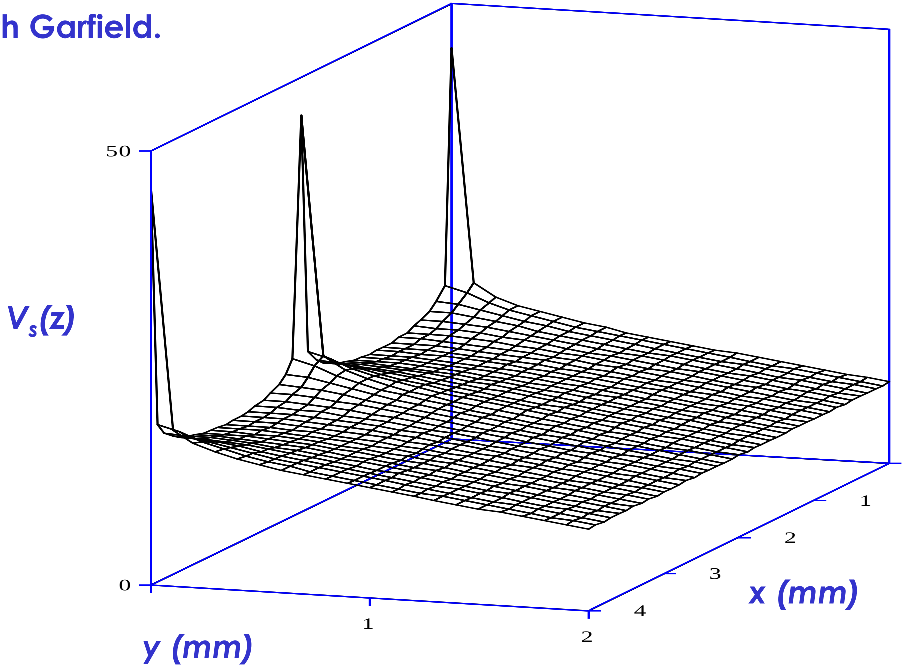
Proportional counter (gain to 10^6); secondary avalanches need to be quenched.
Limited proportionality (secondary avalanches distorts field, more quenching needed).

Geiger Muller mode, avalanches all over wire, strong photoemission, breakdown avoided by cutting HV.



Ionisation Detectors

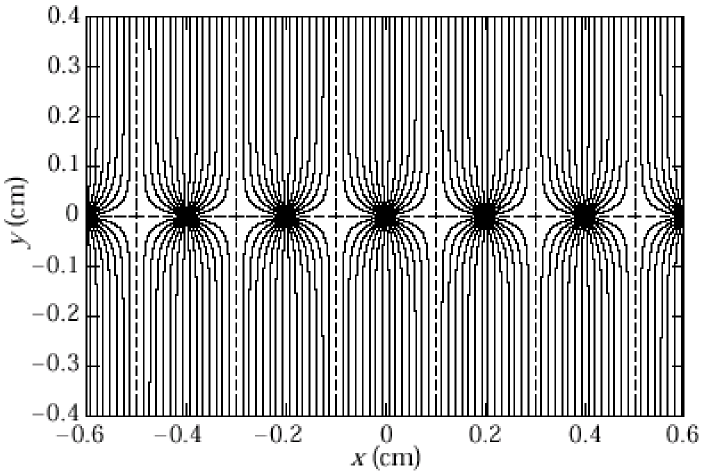
Advanced calculations of electric field, drift, diffusion and signal formation can be done with Garfield.

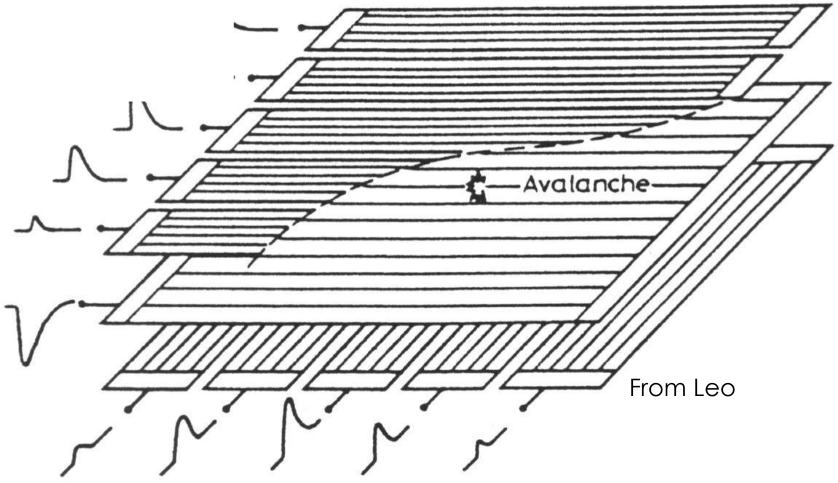


Two dimensional readout can be obtained by; crossed wires, charge division with resistive wires, measurement of timing differences or segmented cathode planes with analogue readout

Resolution given by (binary readout) : $\sigma = d/\sqrt{12}$

Analogue readout and charge sharing can improve this significantly when the left/right signal size provide more information about the hit position.



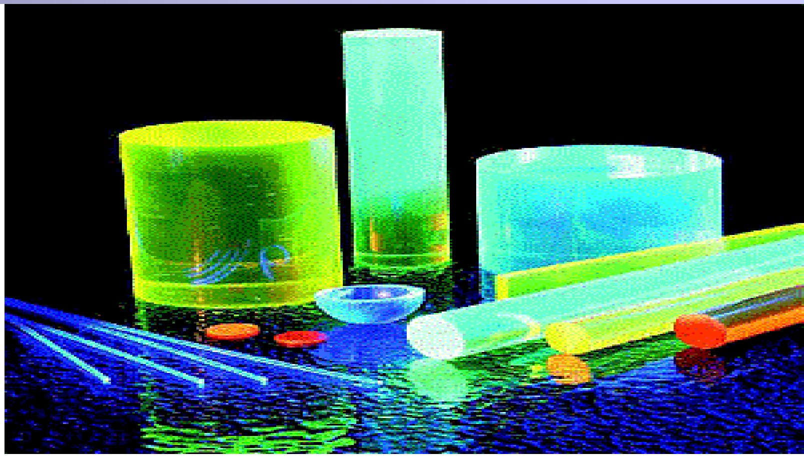


From Leo

$$y = \frac{\sum (Q_i - b)\, y_i}{\sum (Q_i - b)} ,$$

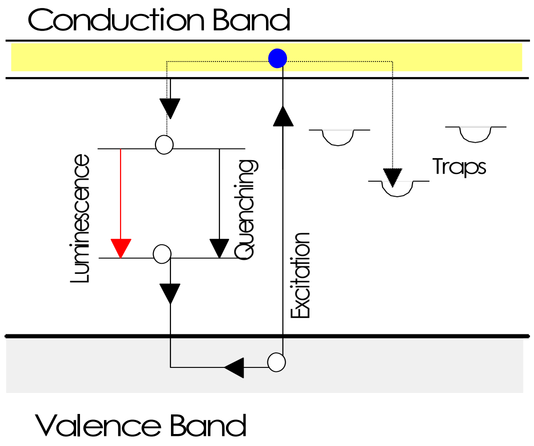
Scintillators

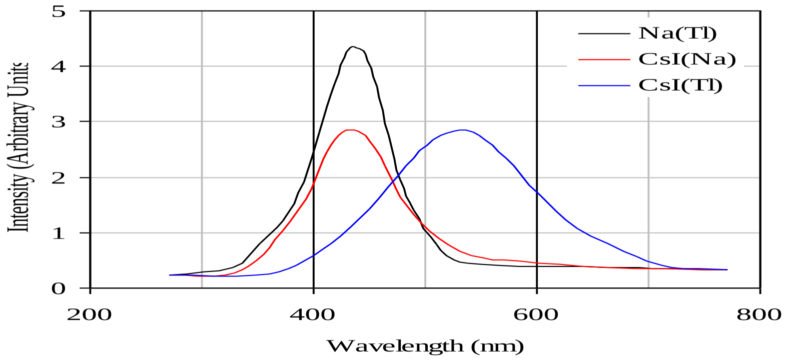
Inorganic Crystalline Scintillators
The most common inorganic scintillator is sodium iodide activated with a trace amount of thallium [NaI(Tl)],



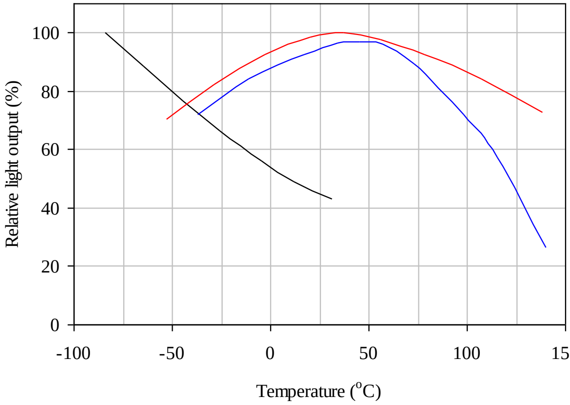
http://www.bicron.com.

Energy bands in impurity activated crystal





Strong dependence of the light output and the decay time with temperature.

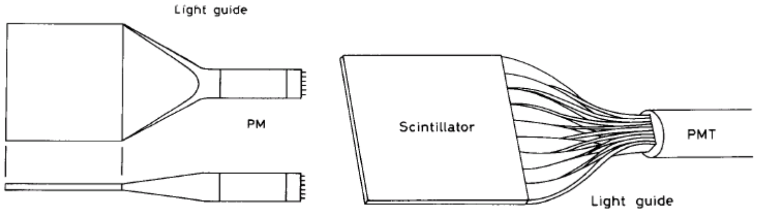


Scintillators

External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov light. See examples.

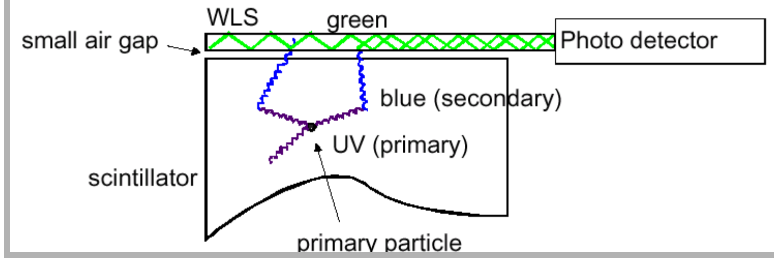
- Light guides: transfer by total internal reflection

  (+outer reflector)



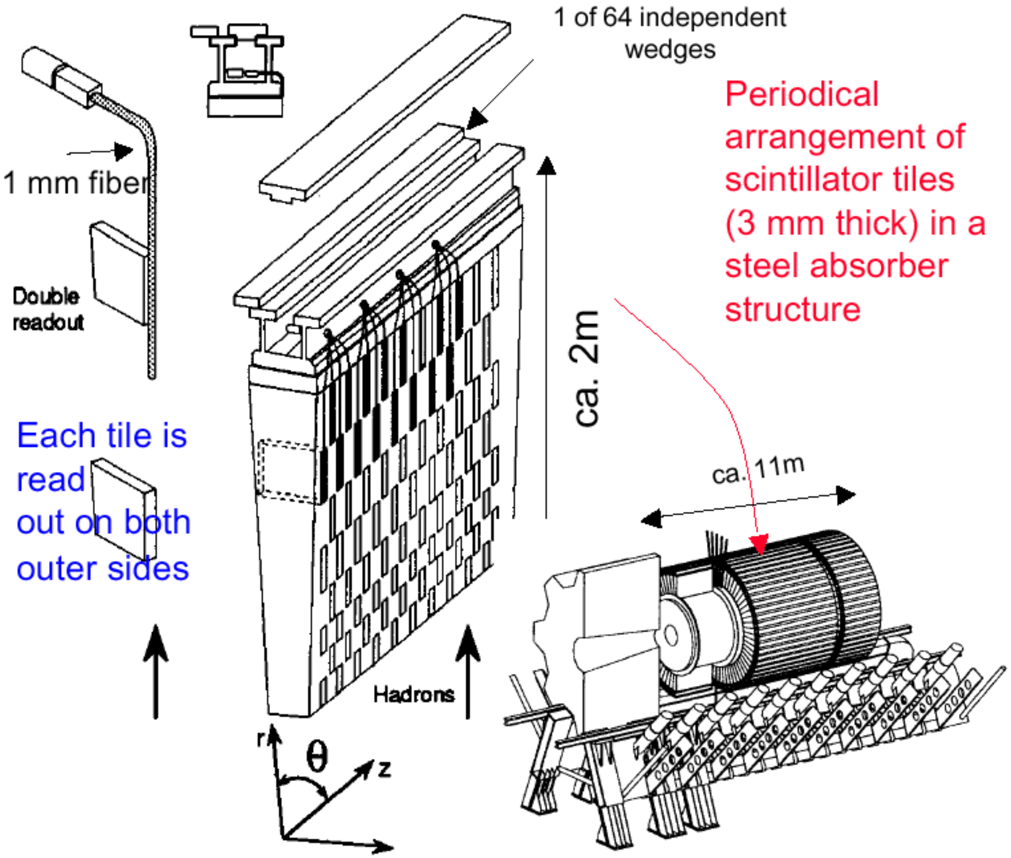
“fish tail” **adiabatic**

- wavelength shifter (WLS) bars



ATLAS Hadron Calorimeter: (ATLAS TDR)

Scintillating tile readout via fibers and photomultipliers

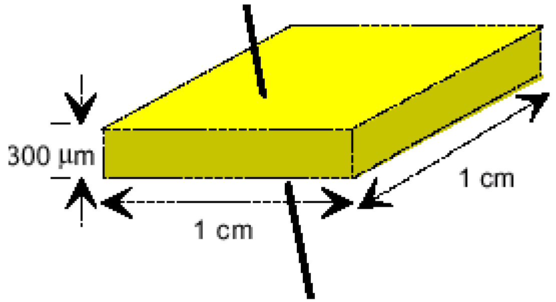


Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure

Each tile is read out on both outer sides

From C.Joram

Semi-Conductors

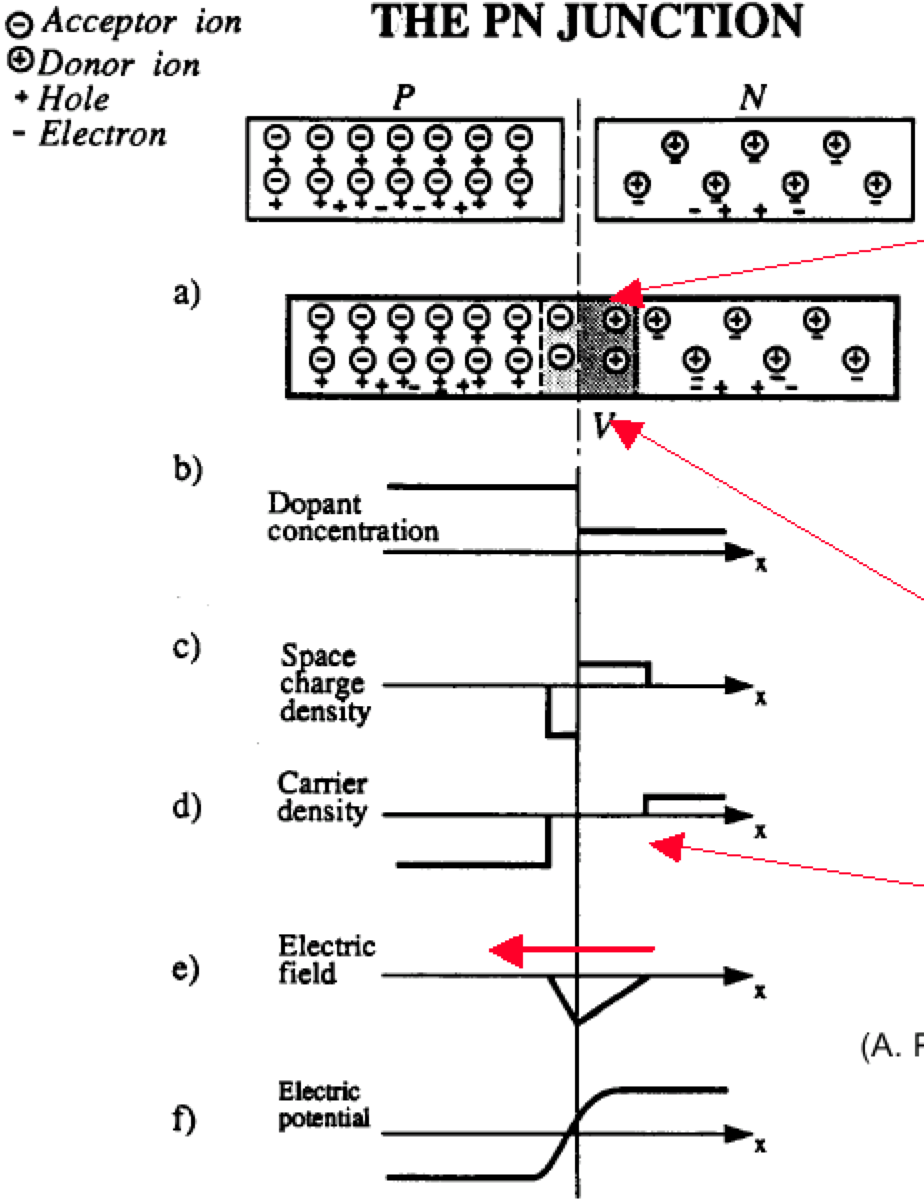


Intrinsic silicon will have electron density = hole density; 1.45 10^{10} cm^{-3} (from basic semiconductor theory).

In the volume above this would correspond to 4.5 10^{8} free charge carriers; compared to around 3.2 10^{4} produces by MIP (Bethe Bloch loss in 300um Si divided by 3.6 eV).

Need to decrease number of free carriers; use depletion zone (reduce temperature would also help but one would need to go to cryogenic temperatures)

Semi-Conductors



diffusion of e^- into p-zone, h^+ into n-zone
→ potential difference stopping diffusion

thin depletion zone

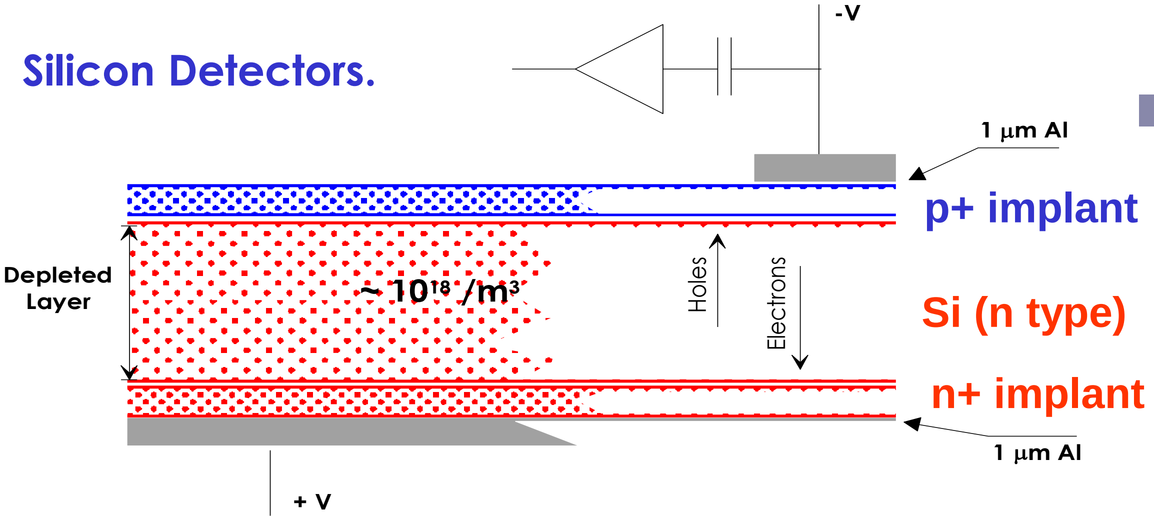
no free charge carriers
in depletion zone

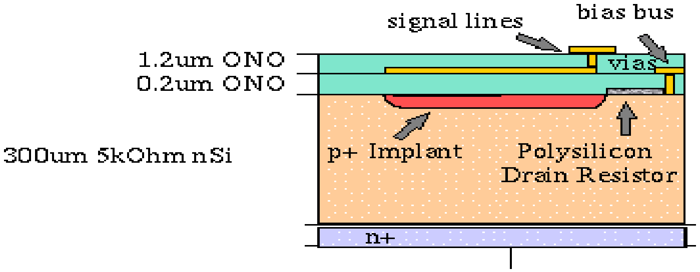
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

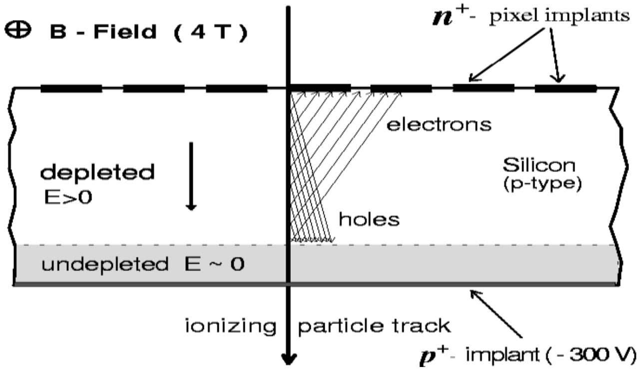
Semi-Conductors

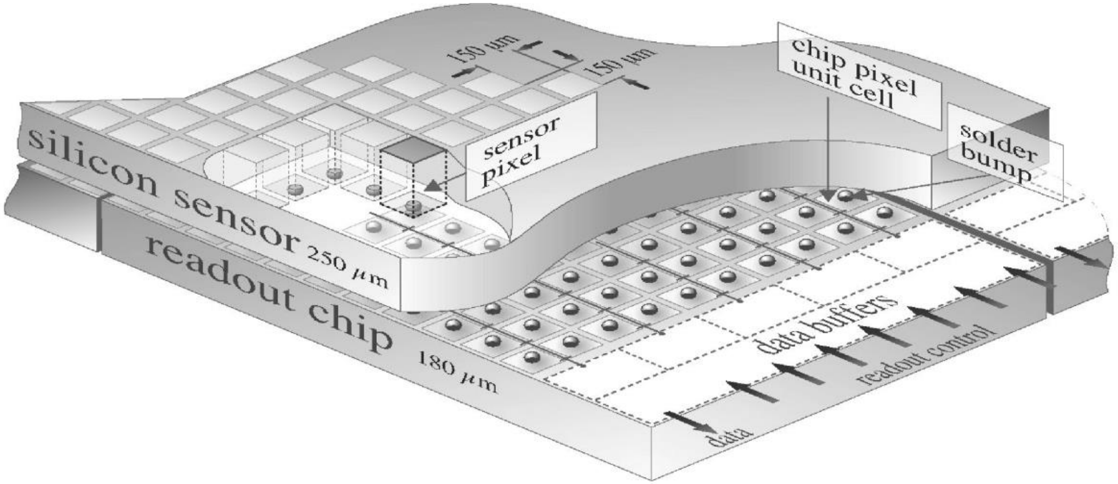
Silicon Detectors.

From CERN-CLAF, O.Ullaland



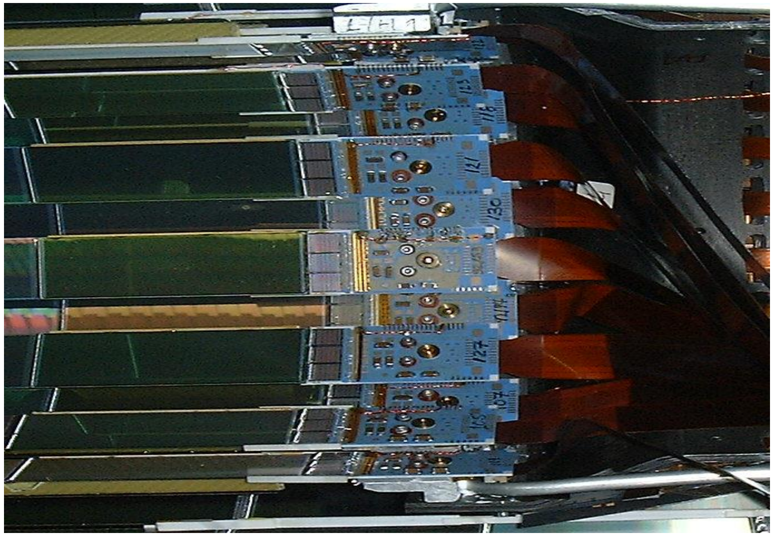




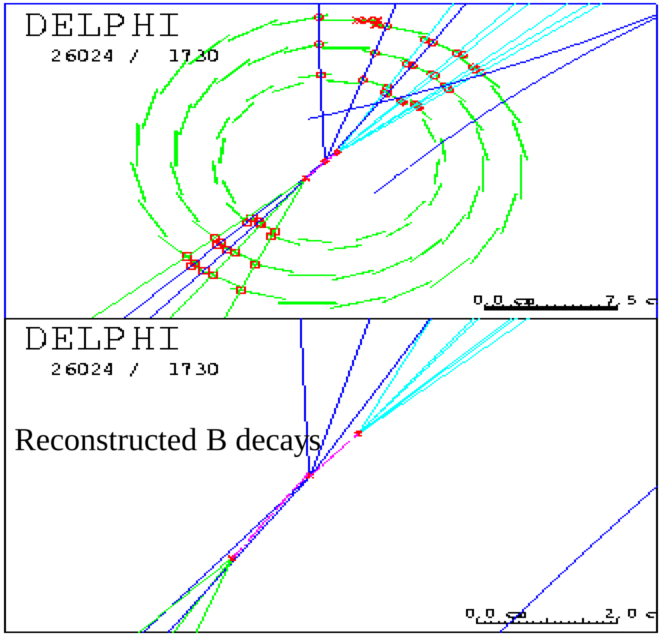


Semi-Conductors

The DELPHI Vertex Detector

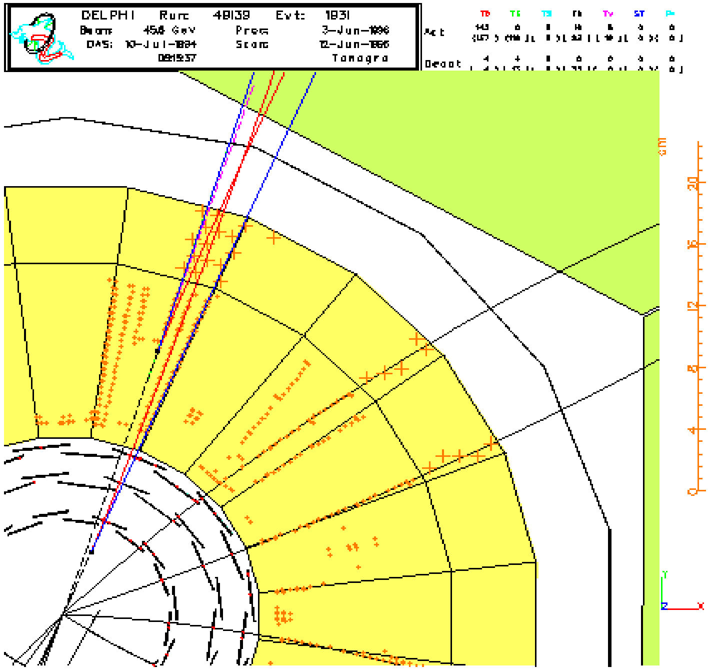


From CERN-CLAF, O.Ullaland



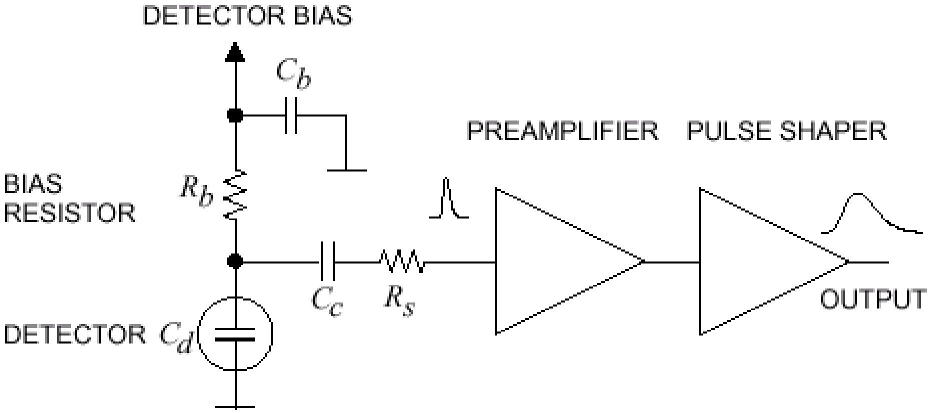
Reconstructed B decays

K0 and Lambda reconstruction



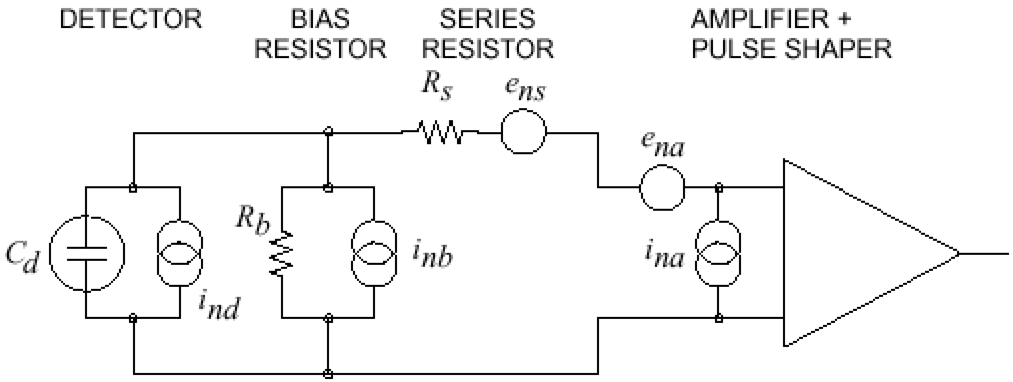
Front End electronics

Most detectors rely critically on low noise electronics. A typical Front End is shown below :



where the detector is represented by the capasitance C_d, bias voltage is applied through R_b, and the signal is coupled to the amplifier though a capasitance C_c. The resistance R_s represent all the resistances in the input path. The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal.

The equivalent circuit for noise analysis includes both current and voltage noise sources labelled i_n and e_n respectively. Two important noise sources are the detector leakage current (fluctuating-some times called shot noise) and the electronic noise of the amplifier, both unavoidable and therefore important to control and reduce. The diagram below show the noise sources and their representation in the noise analysis :



Instrumentation

We now know how most particles (i.e all particles that live long enough to reach a detector; e,u,p,π,k,n,γ, neutrinos,etc) react with matter.

We now know how to identify particles to some extend, how to measure E and p, v, and how to measure lifetimes using secondary vertices, etc

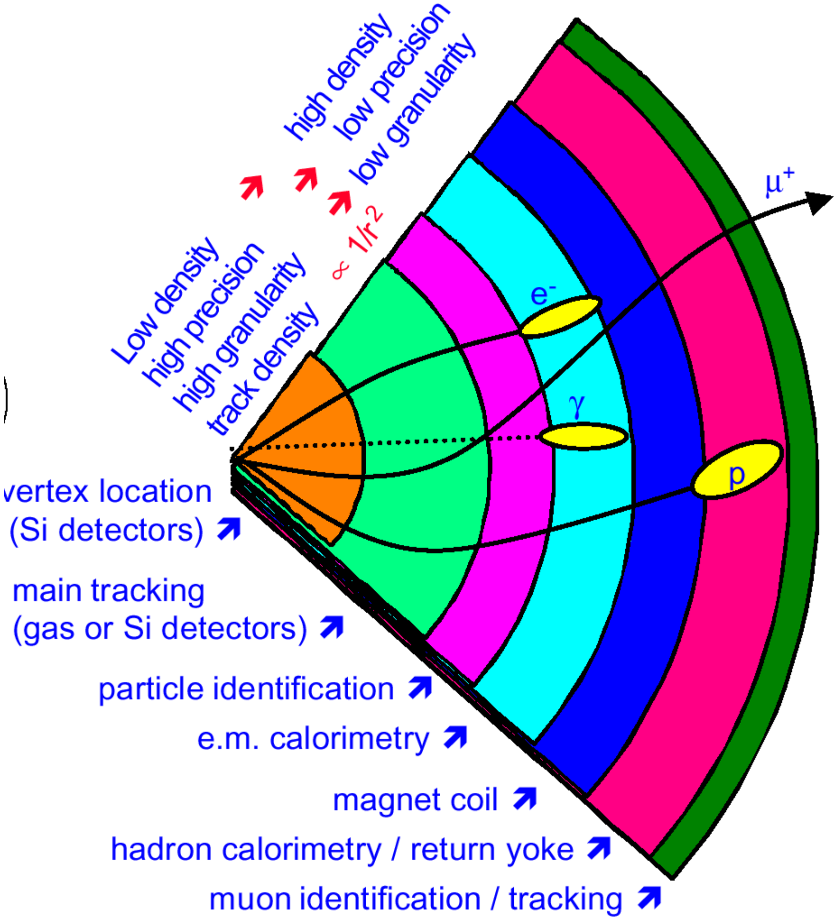
Essential three detector types are used :

1 Ionisation detectors

2 Scintillators

3 Semi Conductors

4 Finally we have looked briefly at how electrical signals are treated in FE electronics



The detector-types mentioned are either for tracking, energy measurement, photon detectors, etc in various configurations.