DETECTORS FOR PARTICLE PHYSICS

Norwegian Physics Teachers @ CERN

Slides from Steinar Stapnes (UiO/CERN)

Presented by Ole Røhne (UiO)

Goals and contents

Goals:

- Motivation: detectors are *crucial* for getting to Frontier Physics but also represent *a field* in its own right
- Detail: detector design is based on a *deep* understanding of particle/ matter interactions
- Overview: extremely complex experiments are however built on *a few* basic detector principles

Contents:

- Interactions of radiation with matter
- Sensors and read-out principles.
- Practical detector systems

Particle physics experimental workflow

Accelerators:

- Luminosity, energy, quantum numbers

Detectors:

- Efficiency, speed, granularity, resolution

Trigger/DAQ:

- Efficiency, compression, through-put, physics models

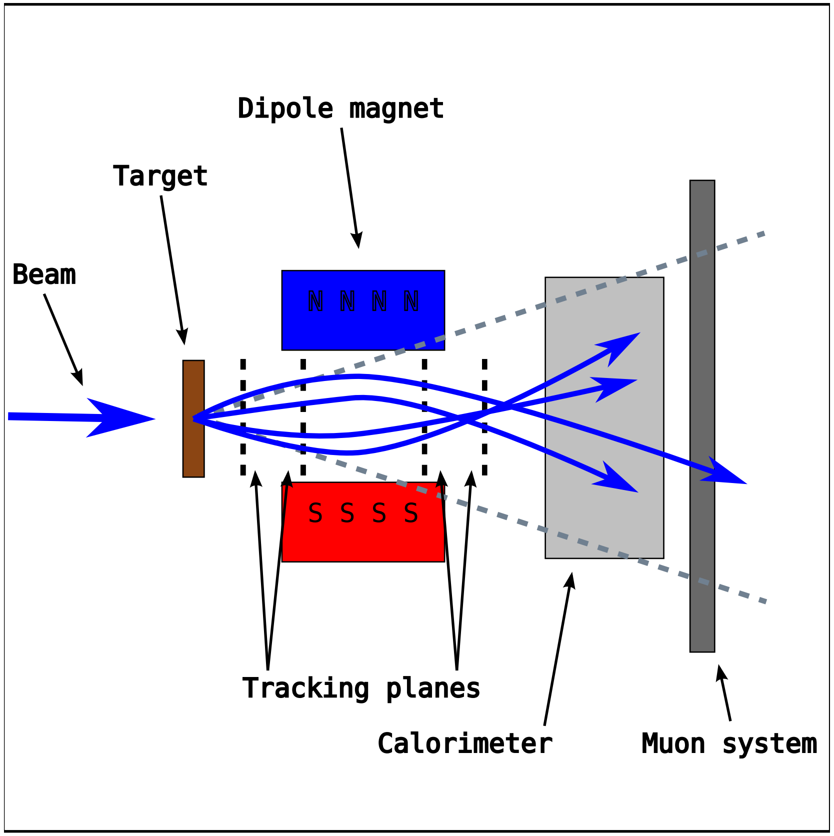
Offline analysis:

- Signal and background, physics models.

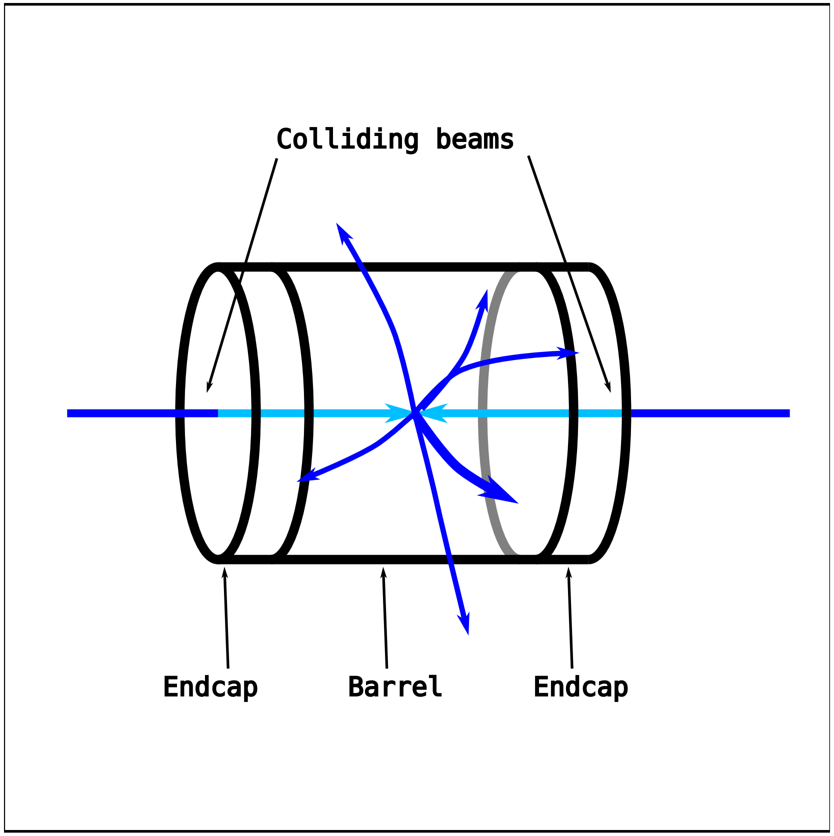
The primary factors for a successful experiment are the **Accelerator,** *and the* **Detector** *and* **Trigger/DAQ** *systems. Losses here are not recoverable.*

Detector systems configuration

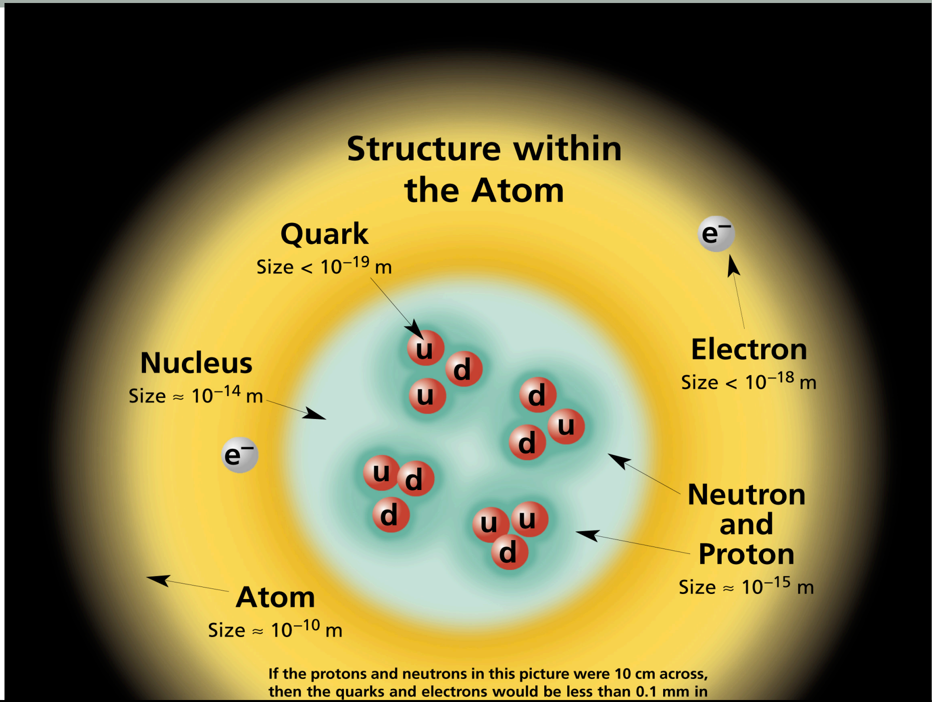
Fixed target
“Magnetic spectrometer”



Collider geometry
“4π hermetic – multi-purpose”



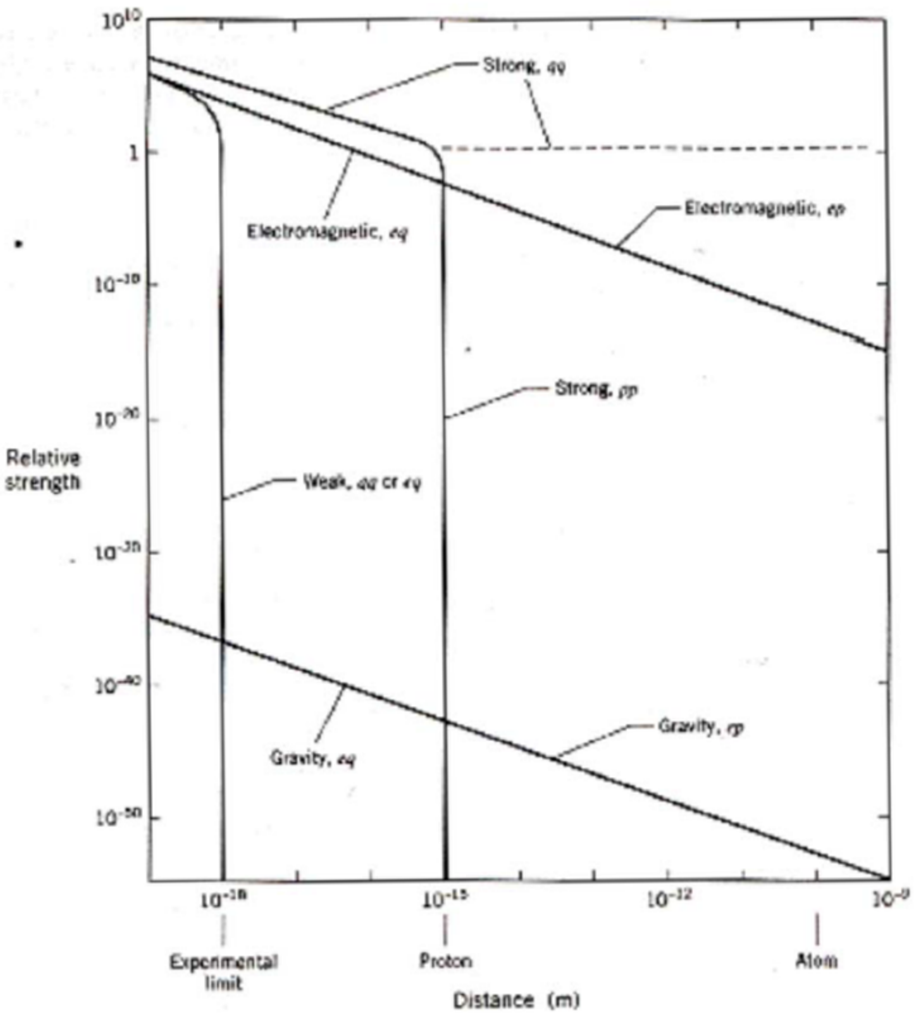
- Focus on electromagnetic forces since they are the primary responsible for energy loss in matter.
- For neutrons and hadrons generally, and neutrinos other effects obviously enter.



PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	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
Strength relative to electromag for two u quarks at: 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



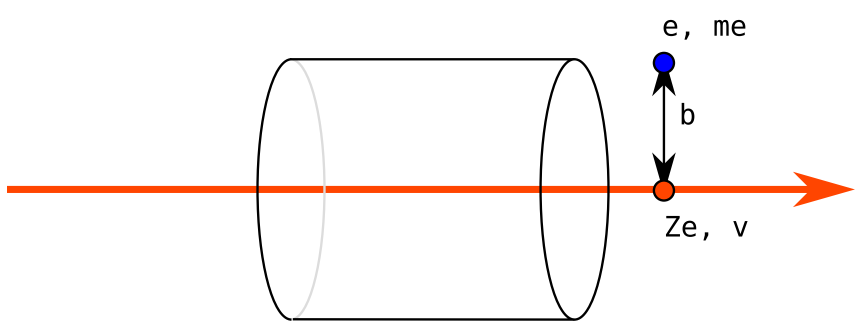
- At atomic distances only EM and gravity have sizeable strength
- EM is ~40 orders of magnitude stronger than gravity
- At proton size distances the strong force turns on and becomes 100x stronger than EM
- At distances 1/1000 of the proton size the weak force turns on abruptly, and has the same strength as EM

Heavy charged particles

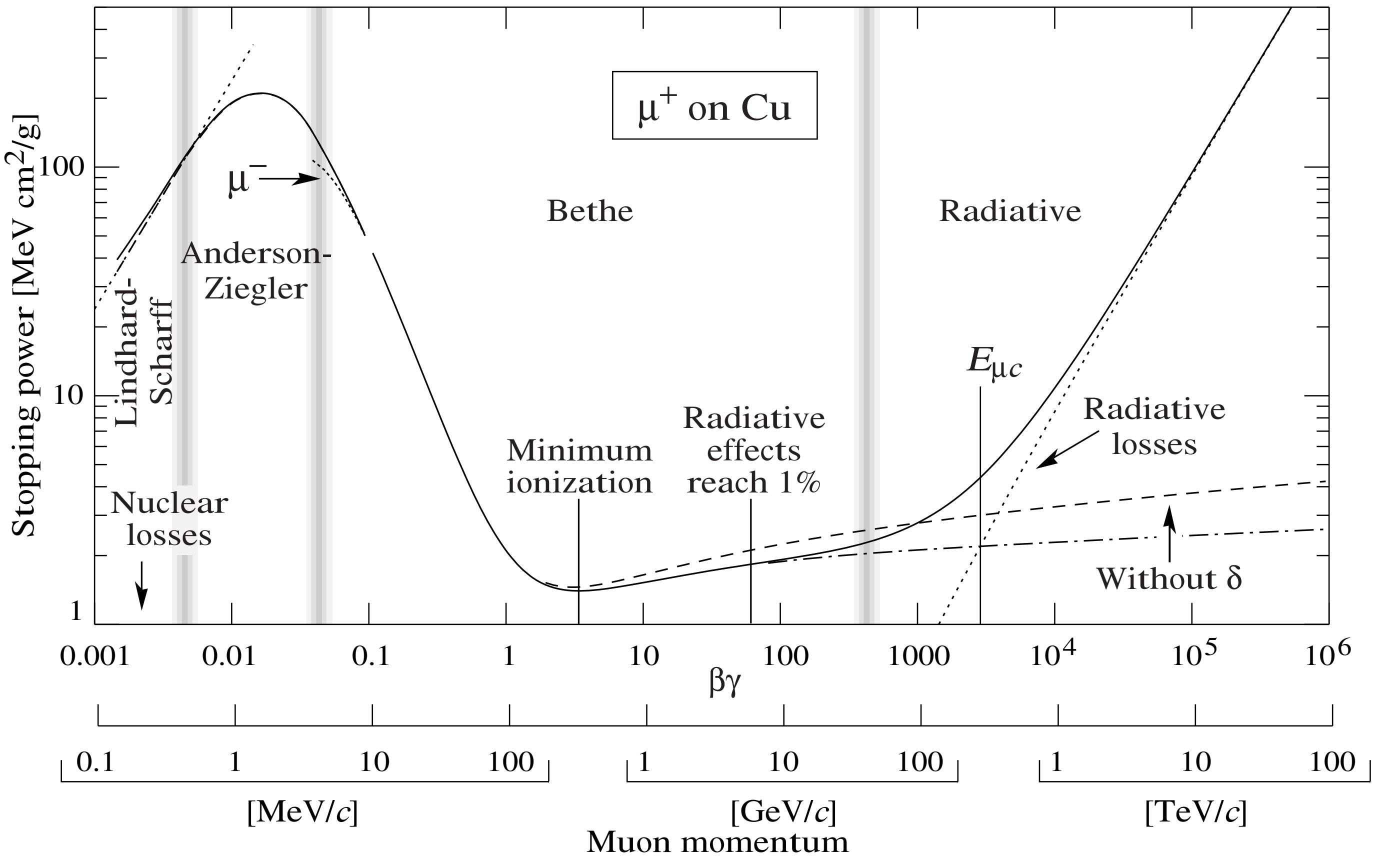
Heavy charged particles transfer energy primarily to atomic electrons, ionizing the atoms (see later for not-so-heavy particles)

The *Bethe-Bloch* formalism is used to describe this – and most of the features can be understood in terms of a simple model:

1) Look at the energy transfer to an electron from a heavy particle passing at distance b
2) Multiply by the number of electrons being passed by
3) Integrate over all reasonable distances b



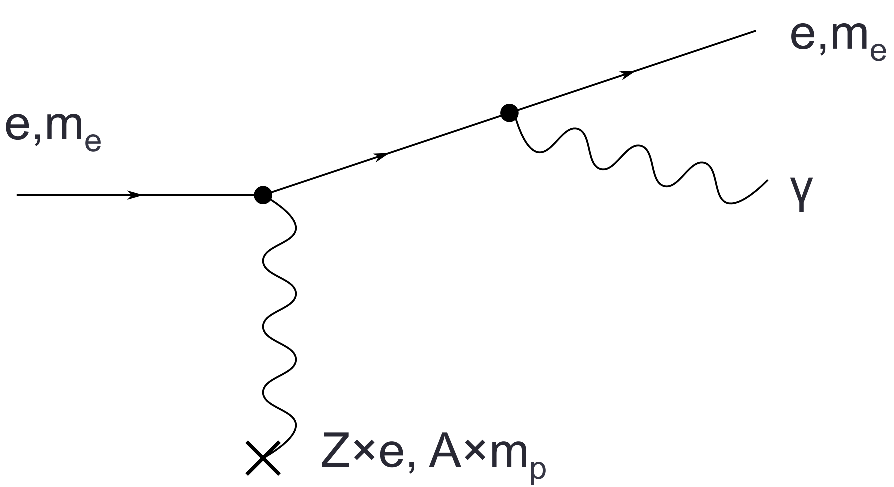
Heavy charged particles

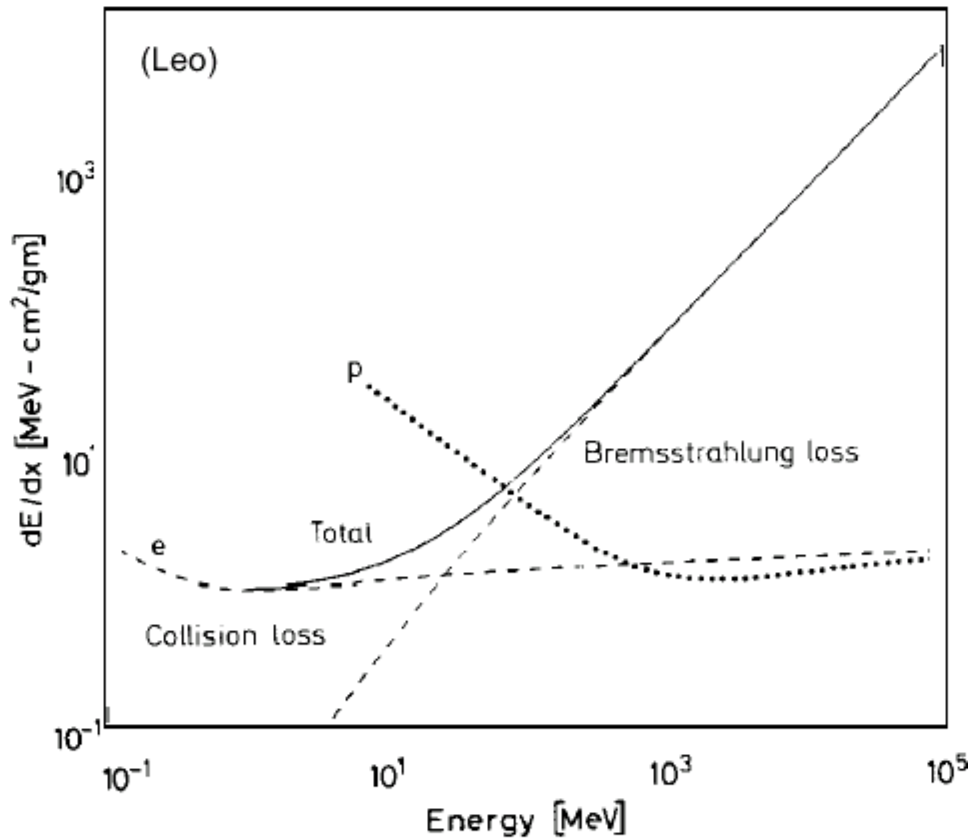


$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Electrons and positrons

- Modify Bethe-Bloch to take into account that the incoming particle has the same mass as the atomic electrons
- Bremsstrahlung in the field of charge Ze; the cross-section goes like $1/m_e^2$





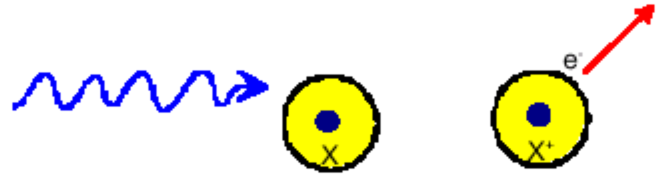
Photons

Three processes:

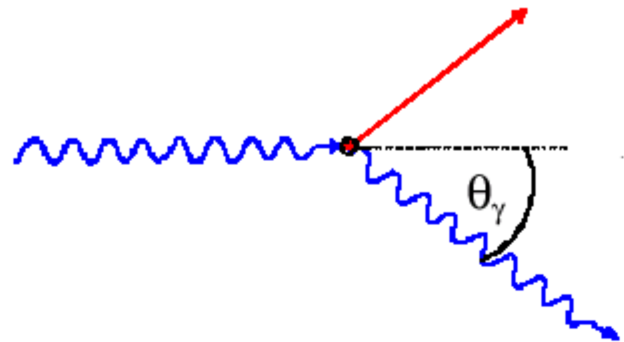
1. **Photoelectric effect (Z^5); absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.**

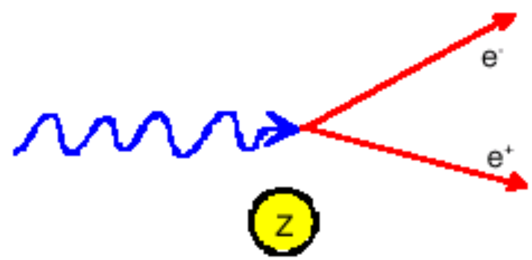
2. **Compton scattering (Z); scattering of a photon again a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc) and for energies above a few MeV 90% of the energy is transferred (in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

3. **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.**



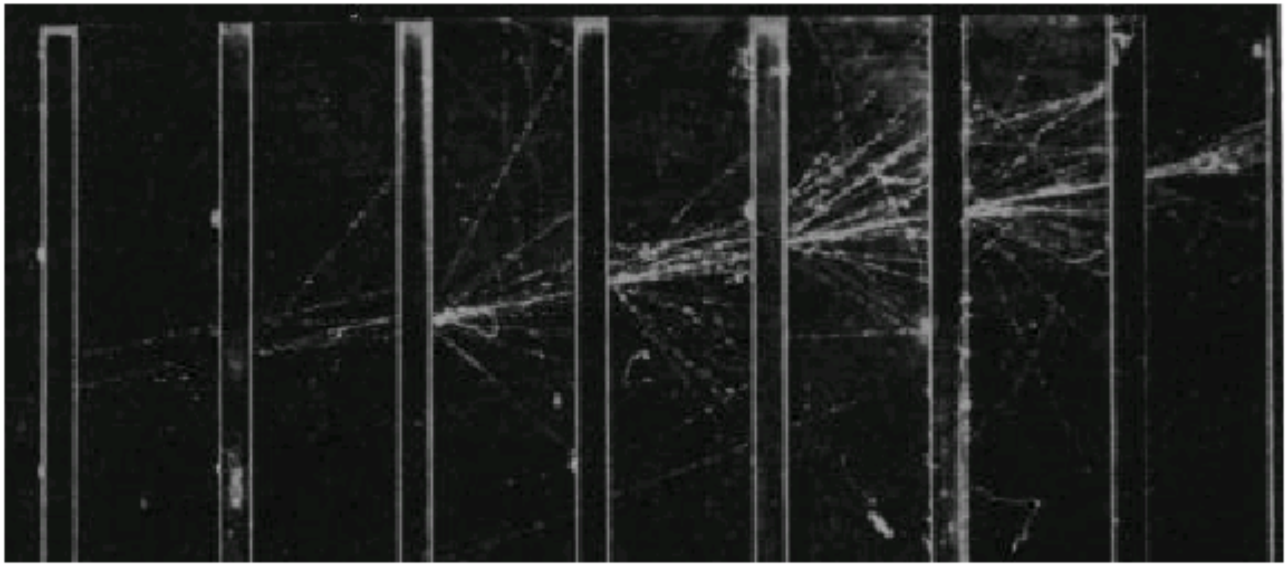
$$\gamma + \text{atom} \rightarrow \text{atom}^{+} + e^{-}$$





(C.Joram)

Electromagnetic calorimeter



Electron shower in a cloud chamber with lead absorbers (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.

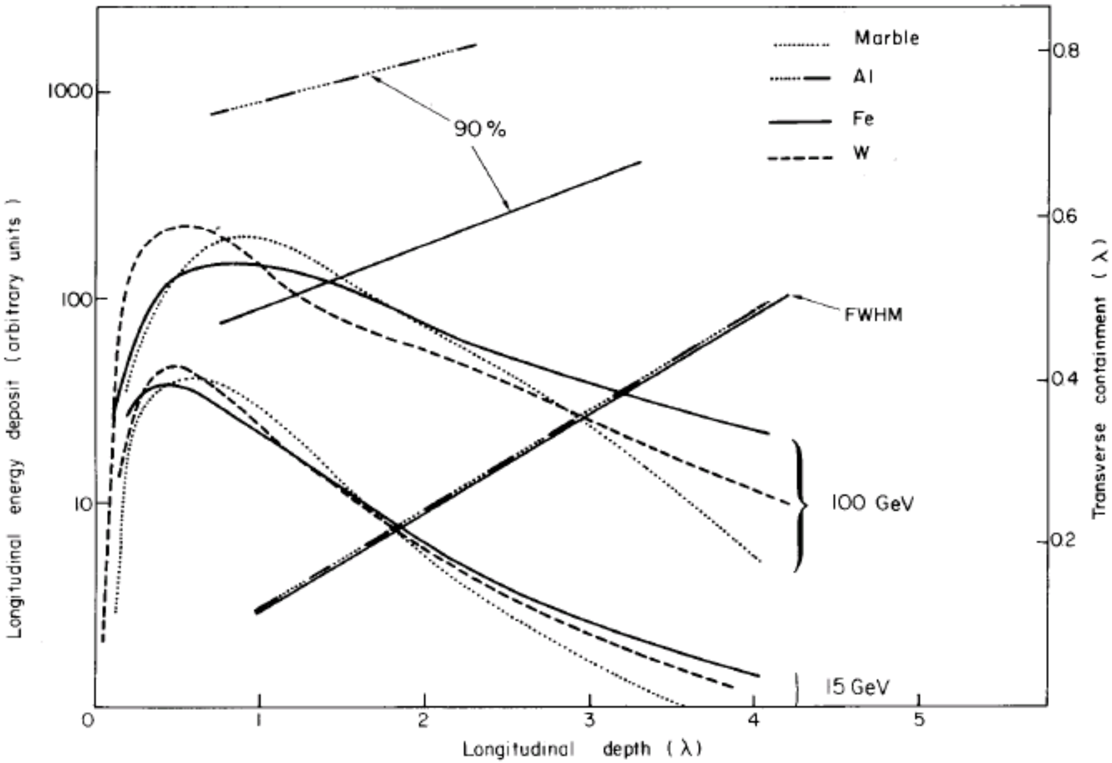
Hadronic calorimeter

Longitudinal shower development

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

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

For Iron: a = 9.4, b=39
E =100 GeV
→ $t_{95\%} \approx$ 80 cm



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

- Additional interactions for hadrons (p, π±, K±)
- Introduce nuclear interaction length and hadronic showers

Neutrinos

Neutrinos interact only weakly; that is hardly at all:

- For detection we need first a charged particle, eg from a charged current interaction: $\nu_e + n \rightarrow e^- + p$
- The cross-section is extremely small, example detection efficiency: 1m iron ~5×10^{-17}
- Neutrino experiments require massive detectors (ktons) and high neutrino fluxes

Fully hermetic collider experiments allow indirect detection of neutrinos (or any hypothetical non-interacting particle):

1. Sum up all visible momentum (or transverse energy)
2. Any momentum imbalance is attributed to the non-interacting particle

To be successful, the method requires full coverage at all times!

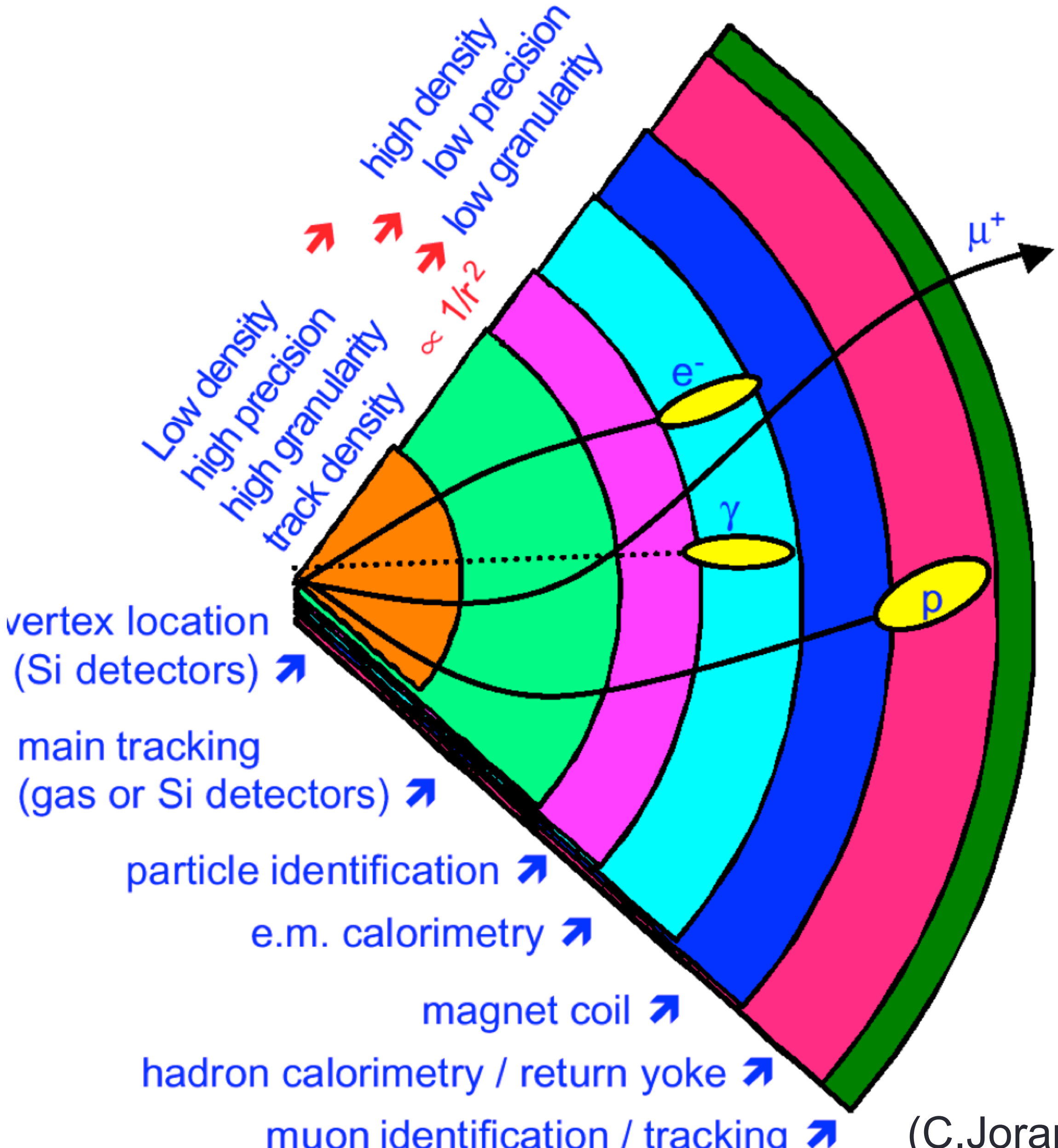
Detector configuration

Various detectors and combination of information can provide particle identification:

Momentum versus EM energy for electrons, EM/HAD provide additional information. Only muons reach the outer detectors.

EM response without tracks indicate a photon.

Secondary vertices identify b,c, τ's. Isolation cuts help to identify leptons

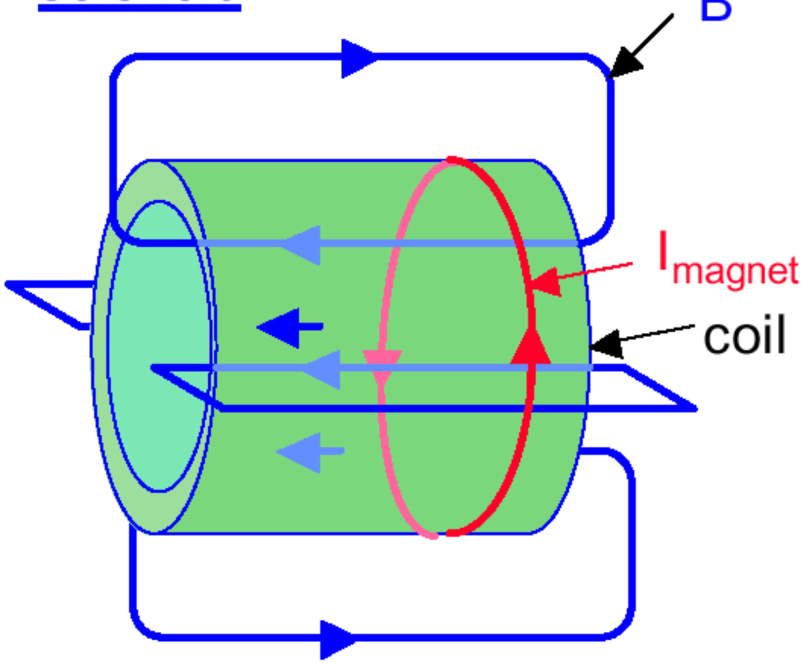


(C.Joram)

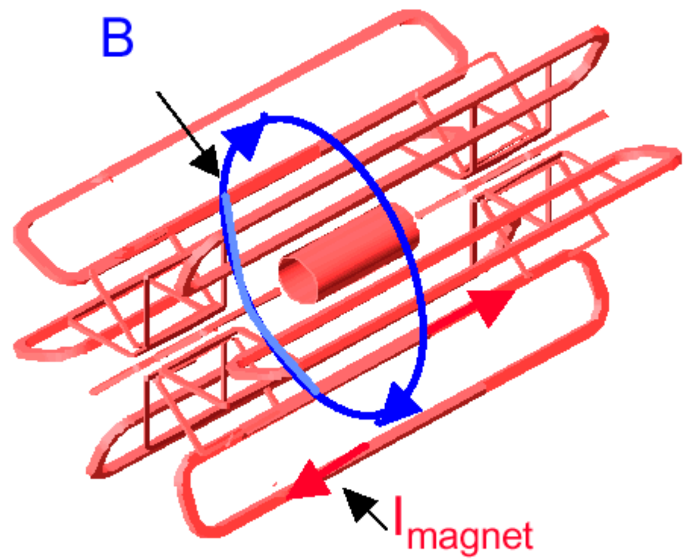
Magnetic fields

Magnetic field configurations:

solenoid



toroid

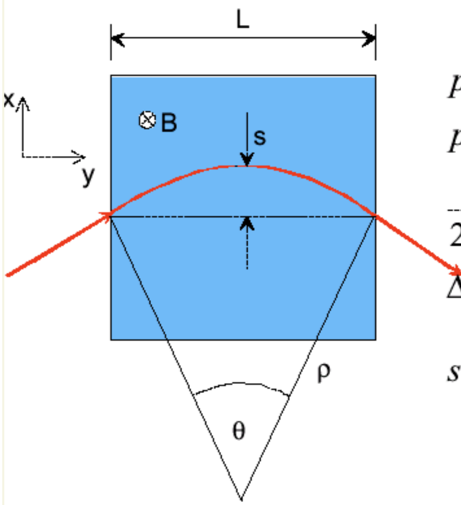


(C.Joram)

The Particle Data Book has a discussion of magnets, stored energy, field, cost etc

Magnetic field

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)

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

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

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

(C.Joram)

Instrumentation

Position- and energy information must be extracted channel-by-channel from the detectors. How are energy deposits of the various particles with detectors turned into electrical signals?

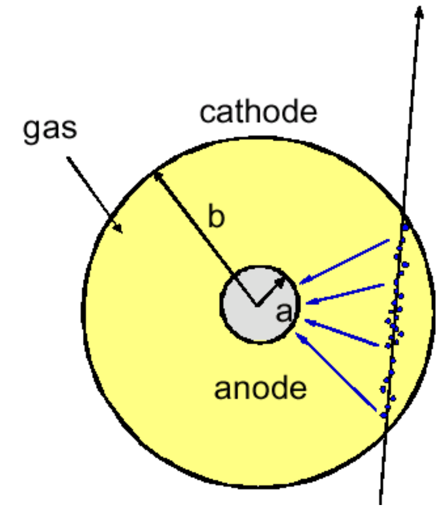
Three effects are commonly used :

- **Ionization detectors**
- **Semiconductors**
- **Scintillators**

Any of the above can be employed for tracking or calorimetry, as well as for photon detectors for Cherenkov or transition radiation

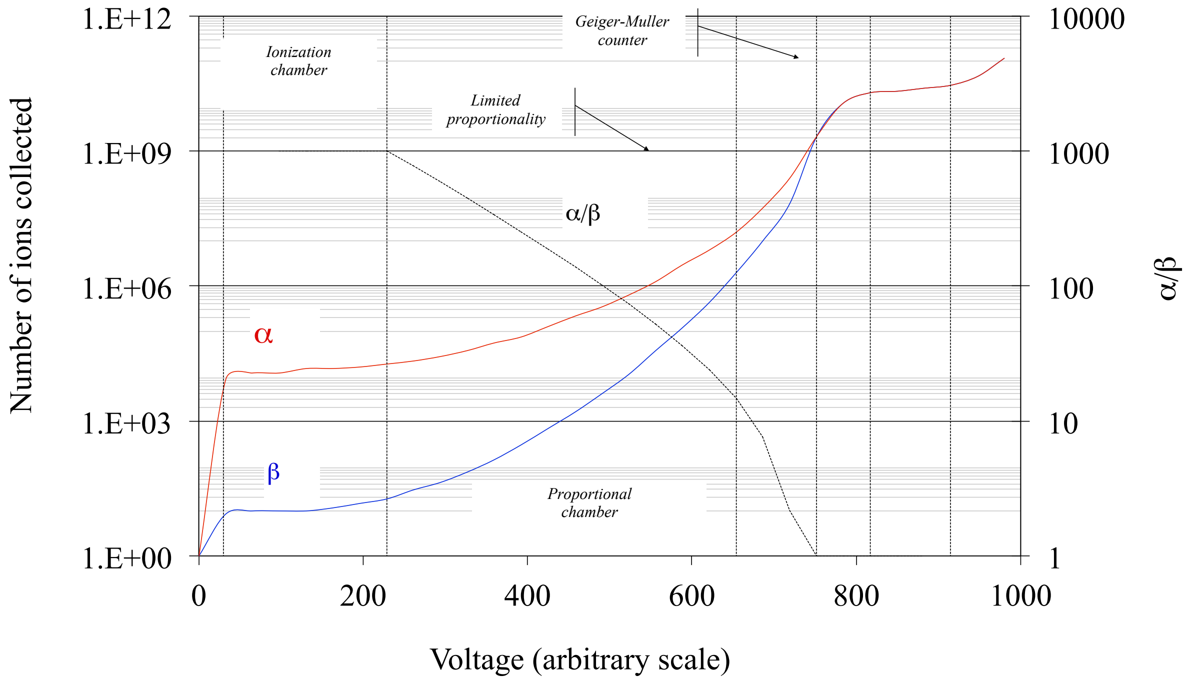
From then on it is all online (trigger/DAQ) and offline processing and analysis

Ionization detectors

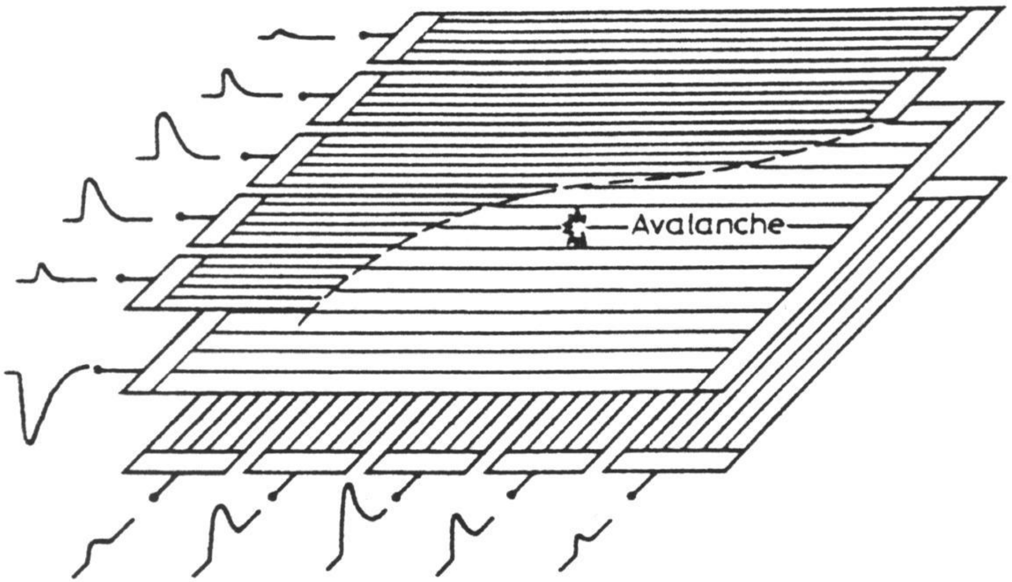


The different regions :

- Recombination before collection.
- Ionisation chamber; collect all primary charges. 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.



Ionization detectors



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

Two dimensional readout can be obtained by:

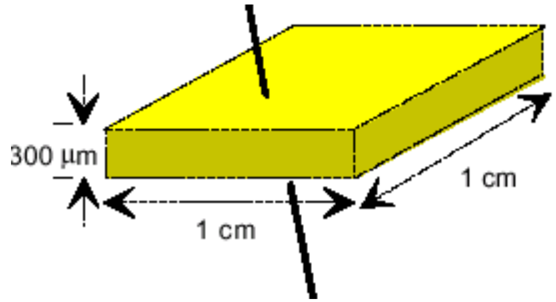
- **crossed wires**
- **charge division with resistive wires**
- **measurement of timing differences**
- **segmented cathode planes with analogue readout**

Resolution (binary readout):

$$\sigma = d / \sqrt{12}$$

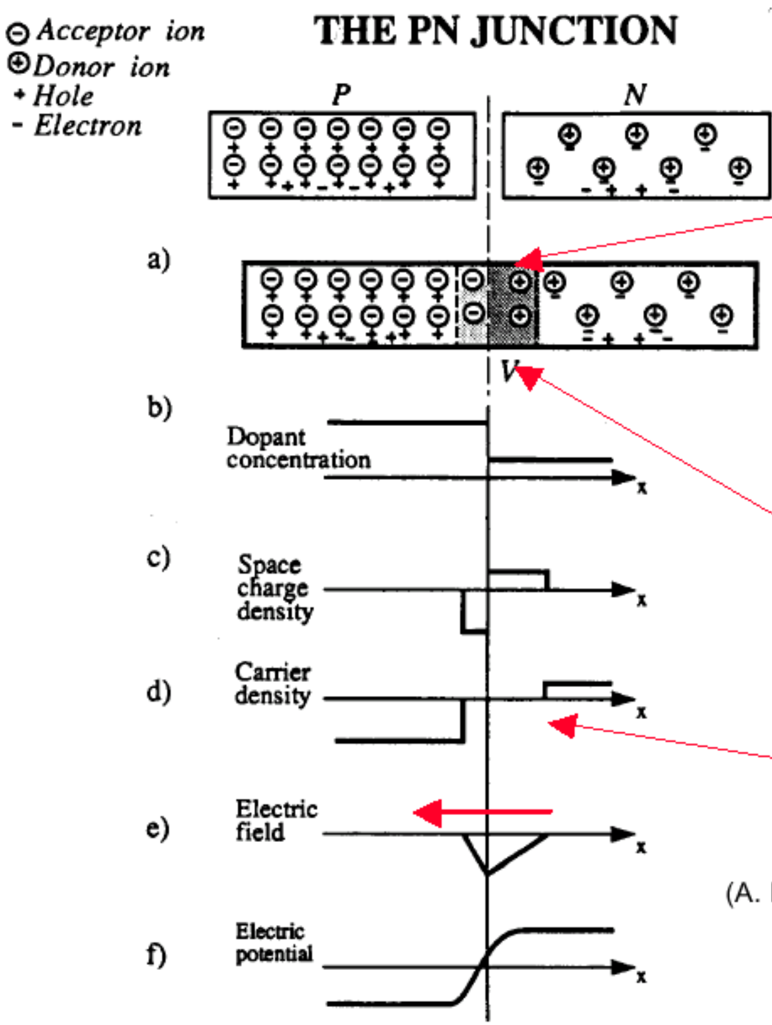
Analogue readout and charge sharing can improve this significantly when the left/right signal size provide more information about the hit position.

Semiconductors



- 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)

Semiconductors



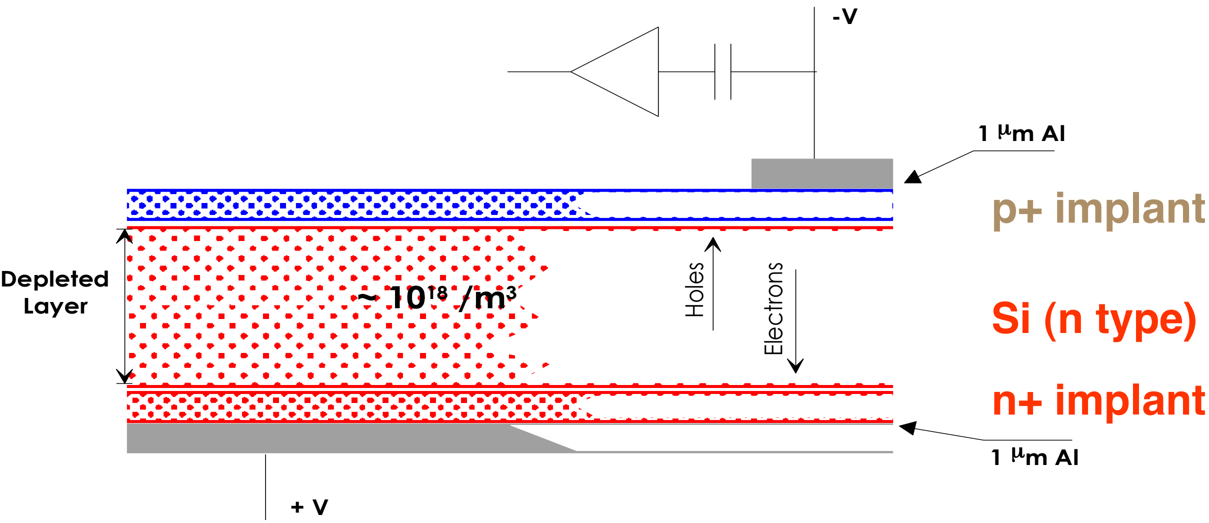
diffusion of e^- into p-zone, h^+ into n-zone → potential difference stopping diffusion

thin depletion zone

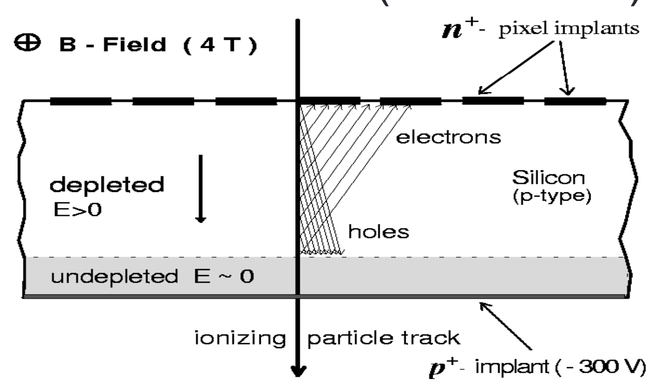
no free charge carriers in depletion zone

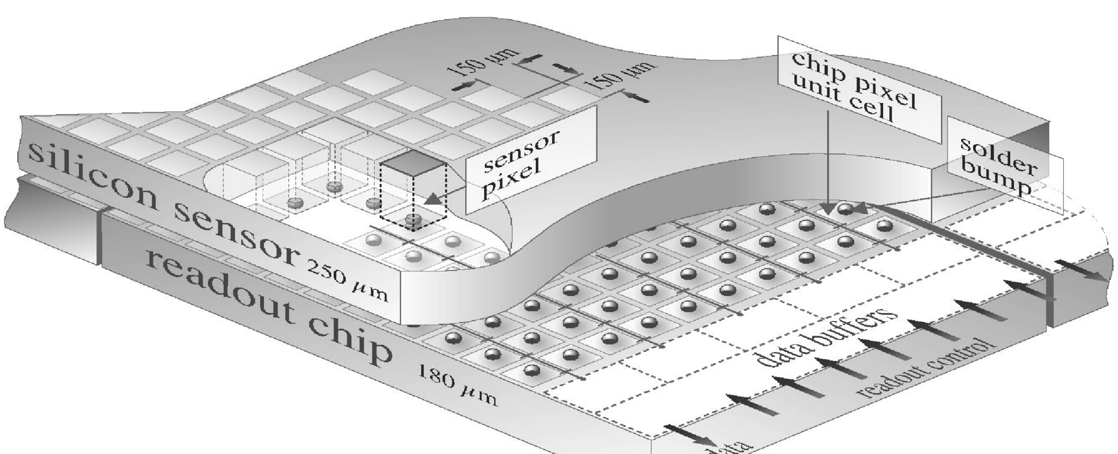
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

Semiconductors



(O. Ullaland)

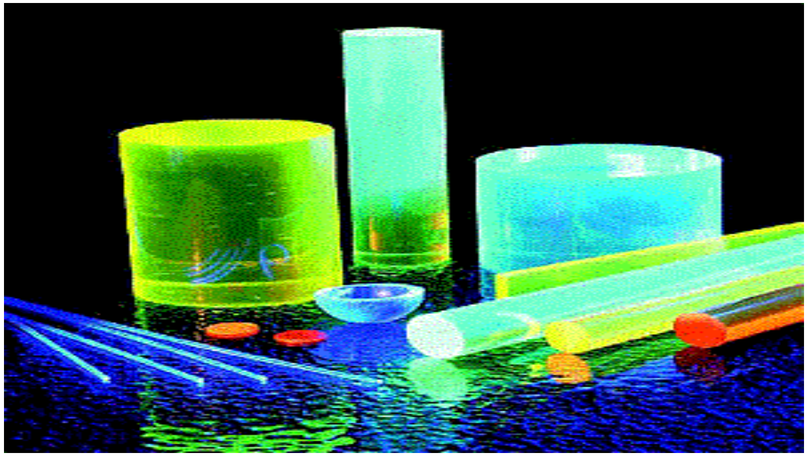




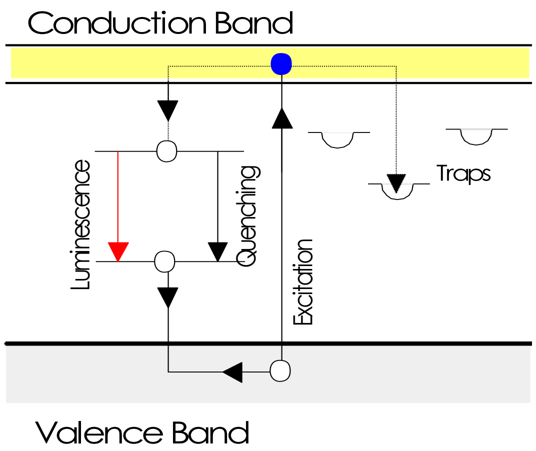
(H. Pernegger, G. Bagliesi)

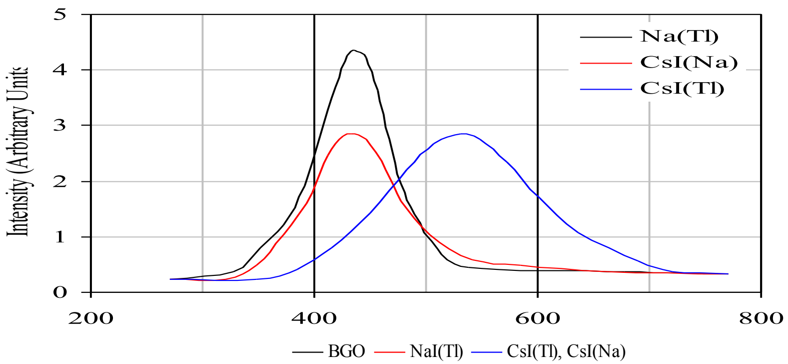
Scintillators

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

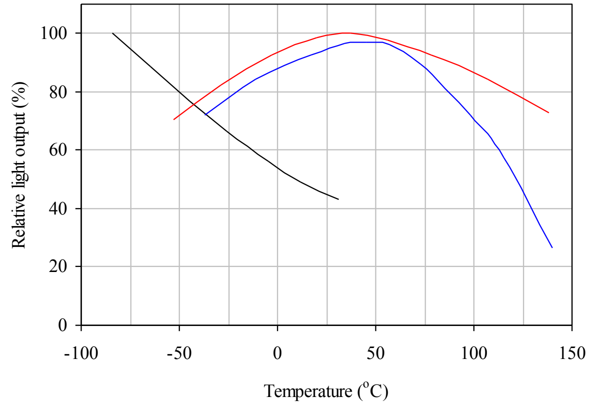


Energy bands in impurity activated crystal





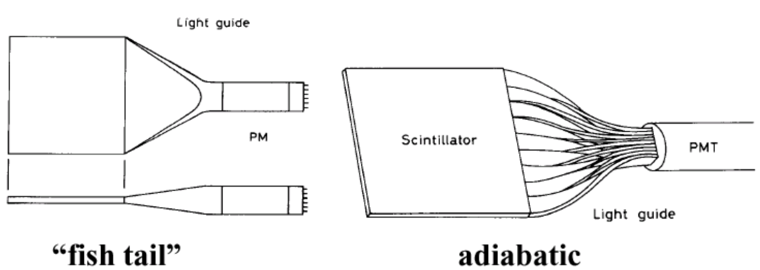
Strong dependence of the light output and the decay time with temperature.



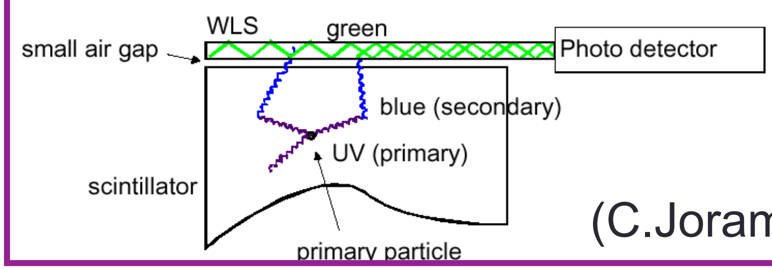
Scintillators

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

- Light guides: transfer by total internal reflection (+outer reflector)



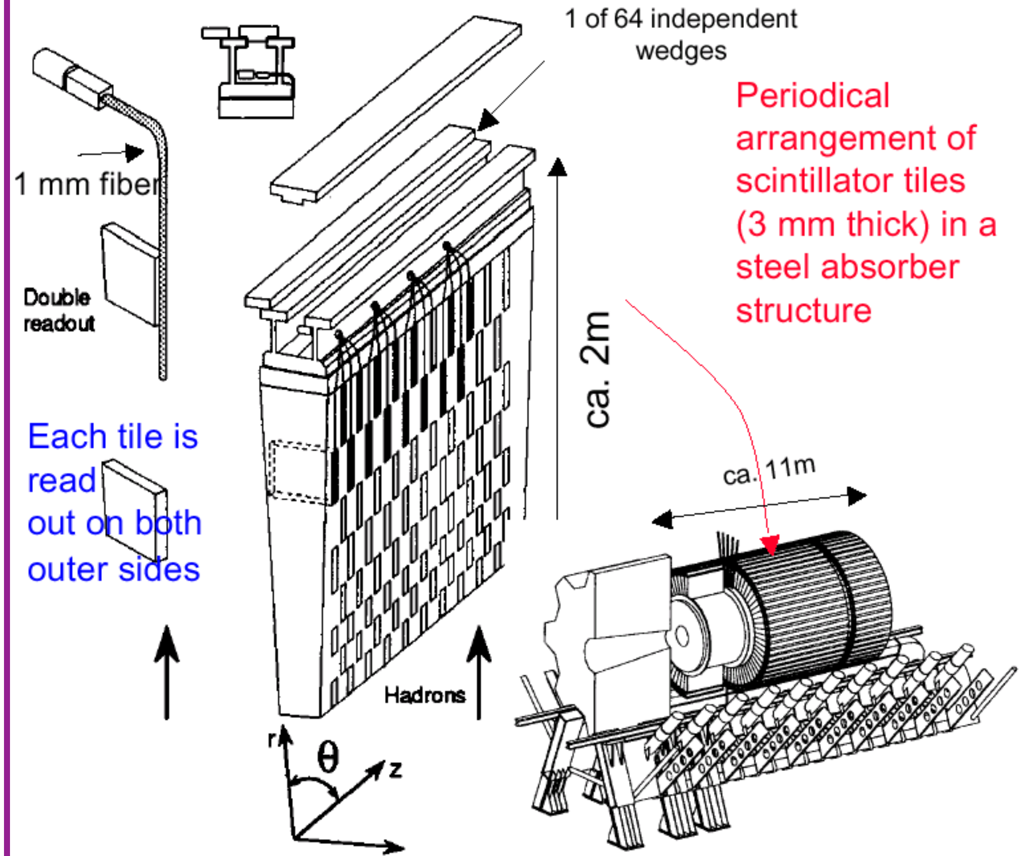
- wavelength shifter (WLS) bars



(C.Joram)

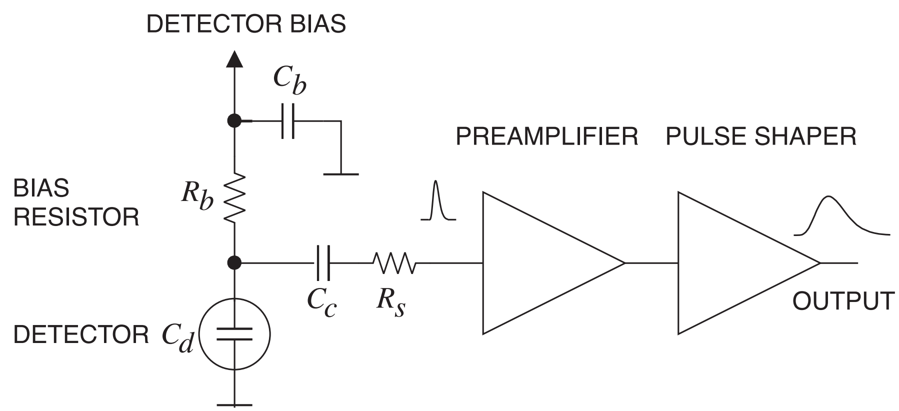
ATLAS Hadron Calorimeter: (ATLAS TDR)

Scintillating tile readout via fibers and photomultipliers



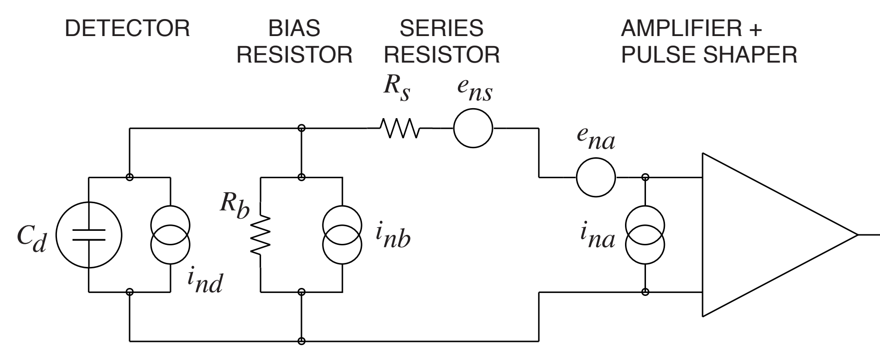
Front-end electronics

Most detectors rely critically on low noise electronics. As a typical example is shown a silicon strip detector with its AC-coupled preamplifier and shaper.



The detector is represented by the capacitance C_d, bias voltage is applied through R_b, and the signal is coupled to the amplifier though a capacitance C_c.

The resistance R_s represents all the resistances in the input path. The preamplifier provides gain and feeds 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 (shot noise) and the thremal noise in R_s.

Summary and final remarks

We have introduced the basic physics of the interactions between particles and matter

- We've focused on charged particle energy loss and calorimeter showers
- Important processes have been ignored: Transition- and Cherenkov radiation…

Detectors at collider experiments are layered to provide:

- Tracking of charged particles
- EM and hadronic calorimetry
- Muon detection.
- Momentum imbalance to trace non-interacting particles

Energy deposits in the active material are converted into electronic signals by several means:

- Ionization and amplification in gaseous detectors
- Semiconductor e/h production
- Scintillation light production

We looked at the challenge of building low noise electronics, and completely ignored a host of other challenges: data rate, material budget, power management, channel mapping, geometric alignment, calibration, channel efficiency, radiation hardness…