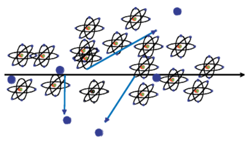
9.2 Detectors

1

Creation of the Signal

Charged particles traversing matter leave excited atoms, electron-ion pairs (gases) or electrons-hole pairs (solids) behind.



1) Excitation:
The photons emitted by the excited atoms in transparent materials can be detected with photon detectors like photomultipliers or semiconductor photon detectors.

2) Ionization:
By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

2

Excitation. Light detection techniques

3

Detectors based on Registration of excited Atoms → ***Scintillators***

Excitation:
The photons emitted by the excited atoms in transparent materials can be detected detectors like photomultipliers or semiconductor photon detectors.

Emission of photons of by excited Atoms, **typically UV to visible light.**

a) Observed in Noble Gases (even liquid !)

b) ***Inorganic Crystals***

→ Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.

c) Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, *organic Scintillators*)

→ Most important category. Large scale industrial production, mechanically and chemically quite robust.

Typical light yield of scintillators:

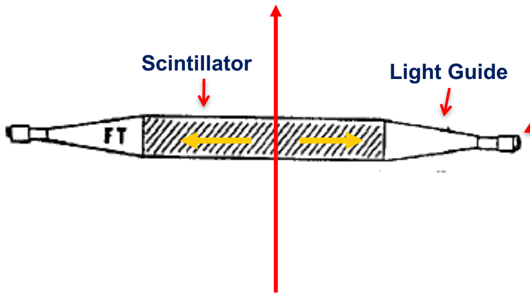
Energy (visible photons 1eV) ≈ few % of the total energy Loss.
Example: 1cm plastic scintillator, $\rho \approx 1$, dE/dx=1.5 MeV,
~15 keV in photons;
~ 15 000 photons **produced.**

4

Scintillators

Photons are being reflected towards the ends of the scintillator.

A light guide brings the photons to the Photomultipliers where the photons are converted to an electrical signal.

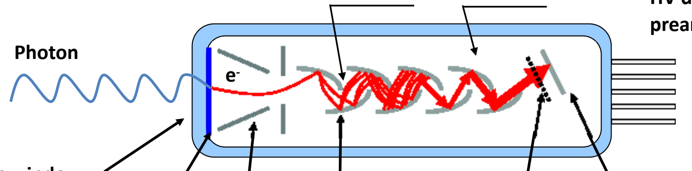


By segmentation one can arrive at spatial resolution.

Because of the excellent timing properties (<1ns) the arrival time, or time of flight, can be measured very accurately → *Trigger, Time of Flight.*

5

Light detection : Photomultiplier tube (PMT)



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Photomultiplier tube (PMT)

PMTs came in many different:
- shapes
- sizes
- performances - given by the large variety of window and photocathode materials and different dynode structures

Advantages

gain: $10^6 \div 10^7$ @ supply voltages of ~ 1 kV

fast response time: ns

large dynamic range: 10^6

Disadvantages

☹ vacuum tube technology (bulky shape)

☹ operates at high voltages: 1 ÷ 2 kV

☹ small quantum efficiency (< 20%)

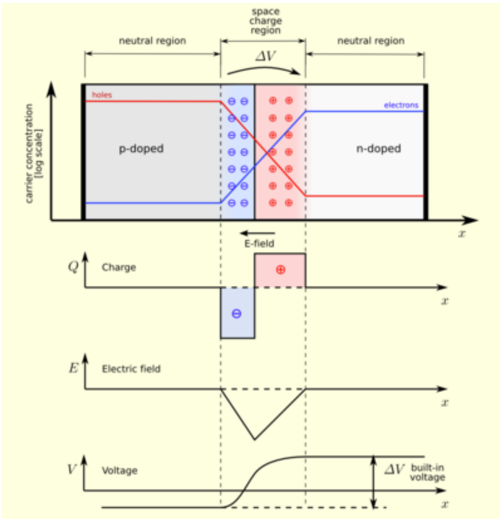
☹ affected by magnetic fields: $B < 10^{-3}$ T

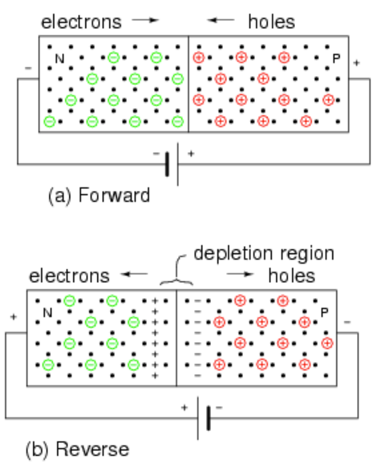
Typical signals:
- **Example: 10 primary Electrons, Gain $10^7 \rightarrow 10^8$ electrons in the end in $T \approx 10$ns. $I=Q/T = 10^8 * 1.603 * 10^{-19} / 10 * 10^{-9} = 1.6$mA.**
- **Across a 50 Ω Resistor → $U=R*I= 80$mV.**

7

Silicon photon detectors – Geiger-Mode Avalanche Diodes (GM-APD)

- pioneering work was done in the 1960s
  - RCA company by J. R. McIntire, IEEE Trans. Electron Devices, ED-13 (1966) 164
  - the Shockley research laboratory by R. H. Haitz, J. Applied Physics, Vol. 36, No. 10 (1965) 3123





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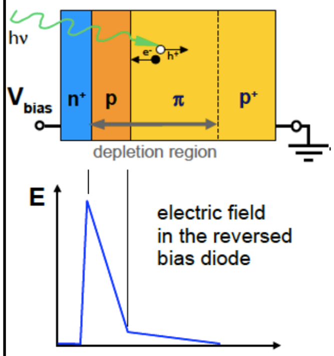
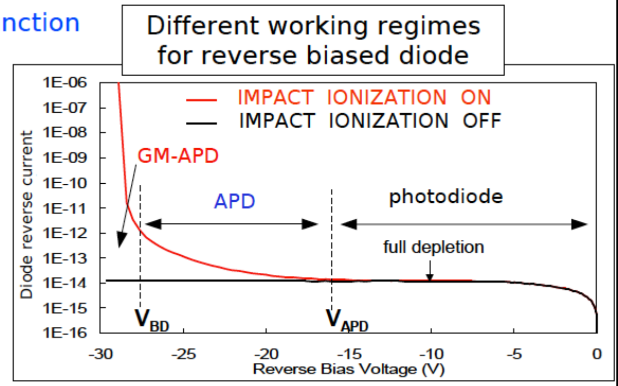
The biulding block of a SiPM: GM-APD

Reverse polarized p-n junction





APD: Linear-Proportional Mode

- Bias BELOW V_{BD} (V_{APD} < V < V_{BD})
- It's an AMPLIFIER
- Gain: limited < 1000 due to fluctuations
- Strong dependence on T and V_{bias}
- No single photo-electron resolution

GM-APD: Geiger Mode

- Bias ABOVE V_{BD} (V-V_{BD} ~a few volts)
- It's a TRIGGER (BINARY) device
- Gain: →∞
- Limited by dark count rate
- Single photo-electron resoution

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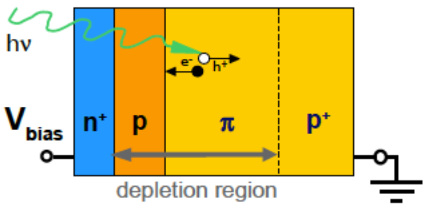
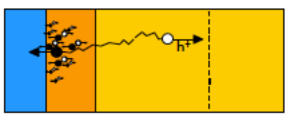
Operation principle of a GM-APD

Diode Biased ABOVE V_{BD}

- t=0: carrier initiate the avalanche

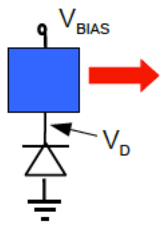


- 0<t<t_1: avalanche spreading



Very fast rise time

- t_1<t: self-sustaining current (limited by series resistances)



To detect another photon need a **quenching mechanism**.
Two solutions:

- Large resistance (passive quenching)
- Analog circuit (active quenching)

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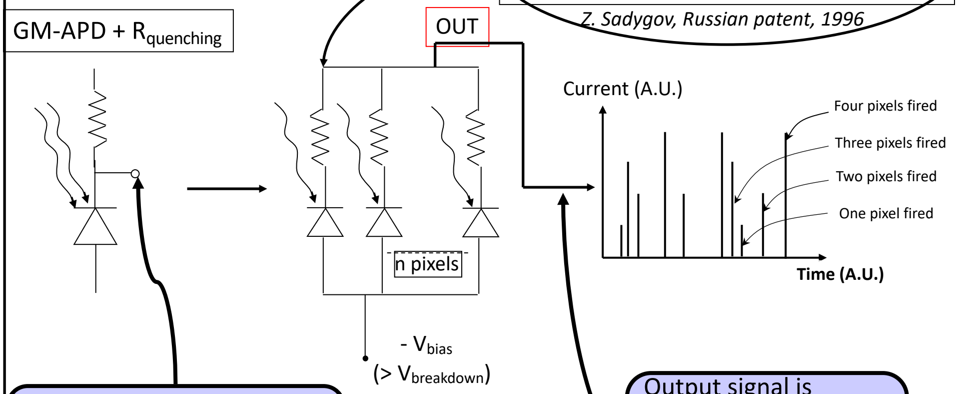
What is a SiPM ?

SiPM

- *matrix of n pixels (~1000) in parallel*
- *each pixel: GM-APD + $R_{quenching}$*

Z. Sadygov, Russian patent, 1996



Output signal is independent of number of photoelectrons (binary device)

Output signal is the sum of the signals from all fired pixels (analogue device)

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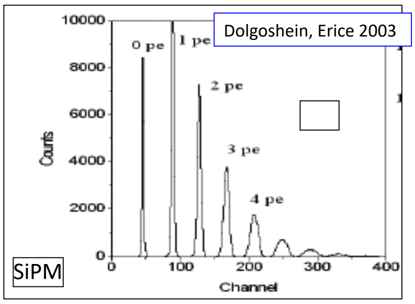
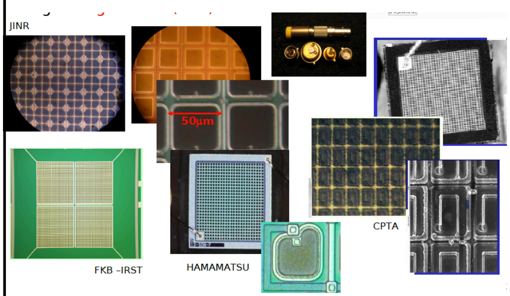
Single photon counting capability

Excellent single photoelectron resolution





Advantages of SiPM:

- low sensitivity against temperature and bias
- very compact
- very robust
- cheap
- insensitive to magnetic fields
- no aging over years
- radiation hard
- very low response to passing ionizing particles

12

Ionization.
Charge detection techniques

Detectors based on Ionization

- Gas detectors
- Solid State Detectors

13

Gas Detectors

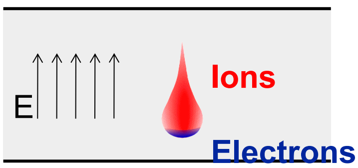
Ionization:
By applying an electric field in the detector volume, the ionization electrons and ions are moving, which induces signals on metal electrodes. These signals are then read out by appropriate readout electronics.

Gas Detectors with internal Electron Multiplication:

Note: At sufficiently high electric fields (100kV/cm) the electrons gain energy in excess of the ionization energy → secondary ionzation etc. etc.

$dN = N\,\alpha\,dx$ **α…Townsend Coefficient**

$N(x) = N_0 \exp(\alpha x)$ **$N/N_0 = A$ (Amplification, Gas Gain)**



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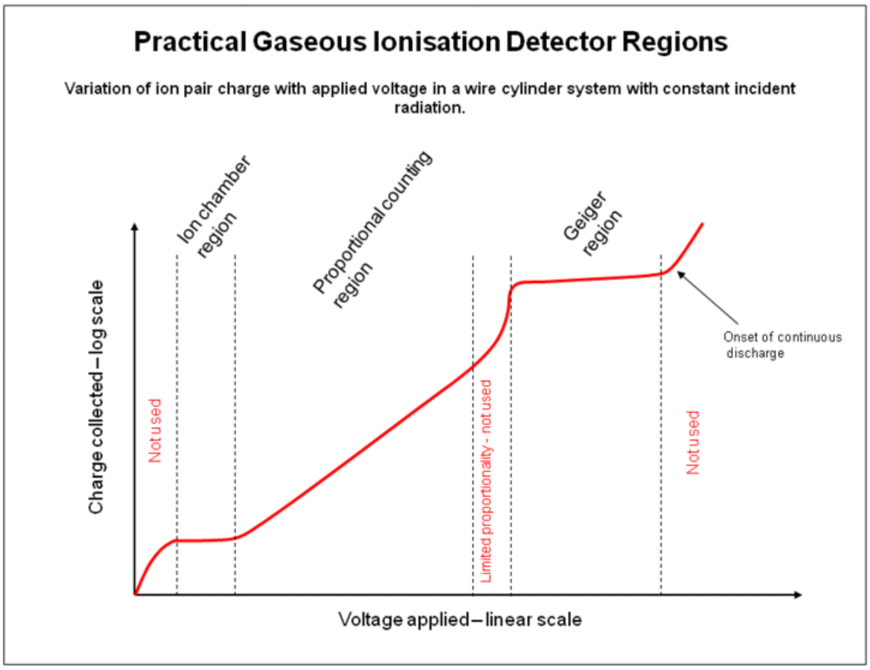

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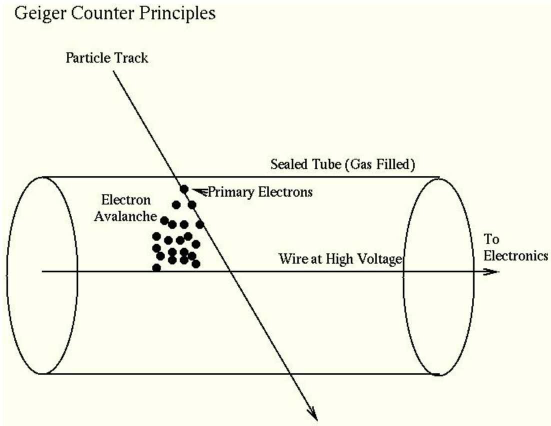
Example: Geiger



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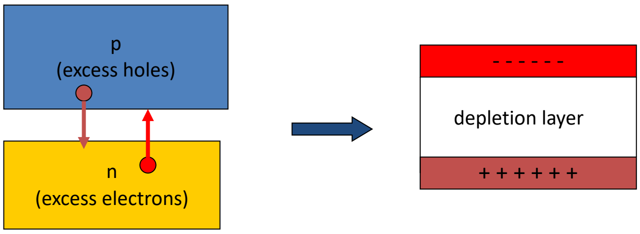
Solid State Devices

Silicon Devices have been developed in the last 2 decades.
Increase spatial precision from O(100 μm) to 0(10 μm)

Ionization detection in silicon (**3.6 eV** per electron hole pair)
rather than gas (**30 eV** ionization potential)

p doped (excess holes) in contact with n doped (excess electrons)
forms a diode. Apply a reverse-bias voltage, $V_n > V_p$.
Very little current flow (few electrons in p doped region).



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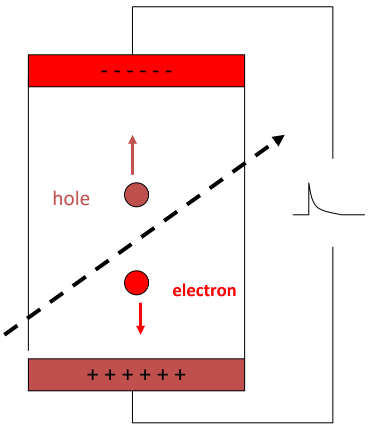
Solid State Devices

Ionizing particle creates electron/hole pair in the depletion layer

Electron/hole drift to the surfaces, where they are majority carriers and can escape to electrodes.

If connect to electrical circuit get a pulse of charge



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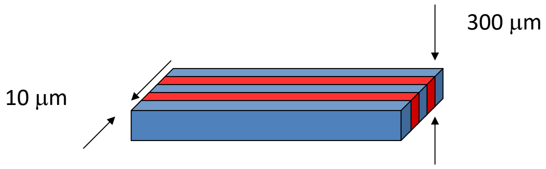
Solid State Tracking Devices

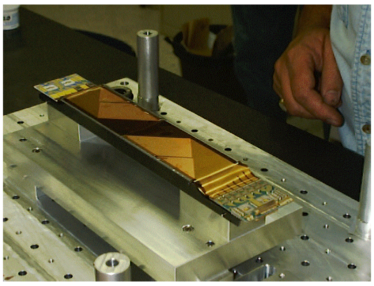
Detectors constructed of strips of width 10 μm to give **O(10 μm) precision**



Construct detector of layers of thin strips.

Some of the electronics is incorporated in the silicon

Very light support structure (low multiple scattering)



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Pixel-Detectors

Problem:

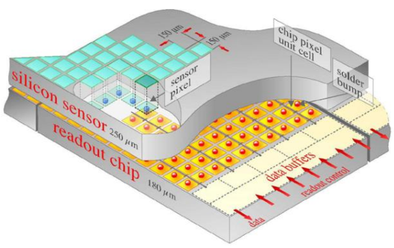
2-dimensional readout of strip detectors results in 'Ghost Tracks' at high particle multiplicities i.e. many particles at the same time.

Solution:

Si detectors with 2 dimensional 'chessboard' readout. Typical size 50 x 200 µm.

Use Bump bonding for coupling the readout electronics to the detector

ATLAS: 1.4×10^8 pixels



Bump Bonding of each Pixel Sensor to the Readout Electronics

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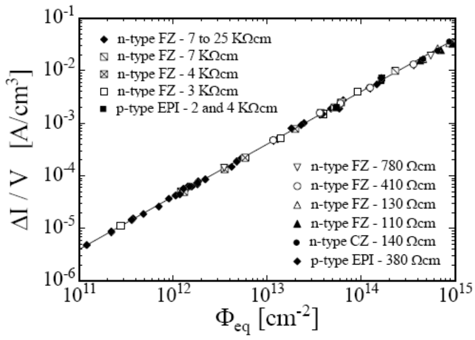
Radiation Effects 'Aging'

Increase in leakage current

Increase in depletion voltage

Decrease in charge collection efficiency



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Towards a general purpose particle detector

A. **TRACKING: Reconstruct momentum of charged particles**
   - Need of magnetic field
   - Low material budget to avoid large multiple scattering and lost of energy
   - **Measure ionization effects on gas or solid devices**
B. **VERTEXING: Reconstruct decay vertices**
   - Very low material budget to avoid large multiple scattering and lost of energy
   - **Measure ionization effects on solid devices with very high position resolution**
C. **PARTICLE ID: Find the type of particle**
   - Measure dE/dx (example: ionization in gas)
   - **Measure Cherenkov light**
   - Combine information of different detectors
D. **CALORIMETRY: Energy measurement by total Absorption of Particles**
   - **ELECTROMAGNETIC calorimeter: energy measurement of electrons and photons**
     Measure energy lost in a dense material (use gas/scintillator to measure a fraction of the ionization energy lost)
   - **HADRONIC calorimeter: energy measurement of neutral and charged hadrons**
     Measure energy lost (including strong interactions with nucleus) in a dense material (use gas/scintillator to measure a fraction of the ionization energy lost)

22

A) Tracking

with

Gas detectors

and

solid Detectors

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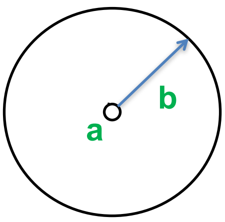
Wire Chamber: Electron Avalanche

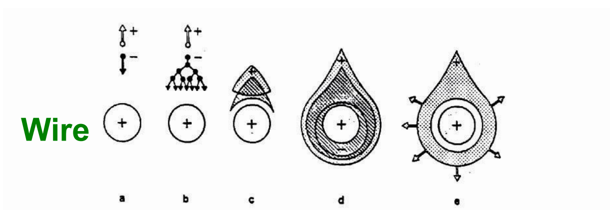
Wire with radius (10-25μm) in a tube of radius b (1-3cm):

$$E(r) = \frac{\lambda}{2\pi\varepsilon_0}\frac{1}{r} = \frac{V_0}{\ln\frac{b}{a}}\frac{1}{r}, \qquad V(r) = \frac{V_0}{\ln\frac{b}{a}}\ln\frac{r}{a},$$

Electric field close to a thin wire (100-300kV/cm). E.g. V_0=1000V, a=10μm, b=10mm, E(a)=150kV/cm

Electric field is sufficient to accelerate electrons to energies which are sufficient to produce secondary ionization → electron avalanche → signal.





The electron avalanche happens very close to the wire

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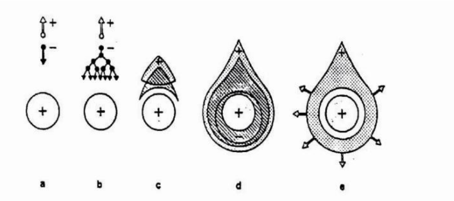
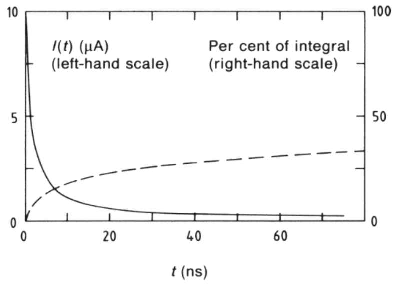
Wire Chamber: Signals from Electron Avalanches

The electron avalanche happens very close to the wire. First multiplication only around R =2x wire radius. Electrons are moving to the wire surface very quickly (<<1ns). Ions are drifting towards the tube wall (typically several 100μs.)

The signal is characterized by a very fast 'spike' from the electrons and a long Ion tail.





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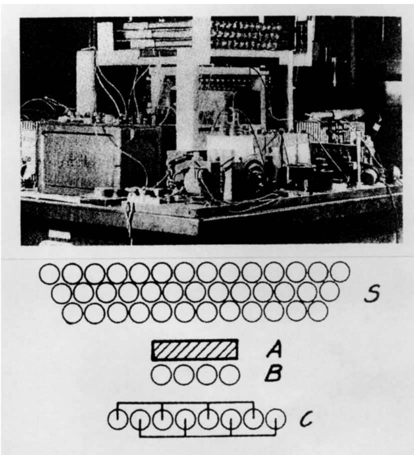
Wire Chamber as tracking device

Cosmic ray telescope 1934



Position resolution is determined by the size of the tubes.

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Multi Wire Proportional Chamber

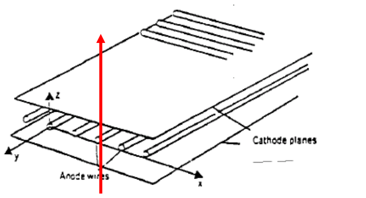
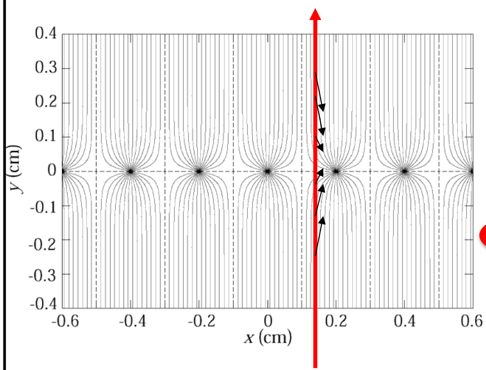


Abbildung 2.27: *Vieldrahtproportionalkammer.*



Classic geometry (Crossection), Charpak 1968 :

One plane of thin sense wires is placed between two parallel plates.

Typical dimensions:

Wire distance 2-5mm, distance between cathode planes ~10mm.

Electrons (v≈5cm/μs) are collected within ≈ 100ns. The ion tail can be eliminated by electronics filters → pulses of <100ns length.

For 10% occupancy → every μs one pulse

→ 1MHz/wire rate capabiliy !

→ Compare to Bubble Chamber with 10 Hz !

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Multi Wire Proportional Chamber

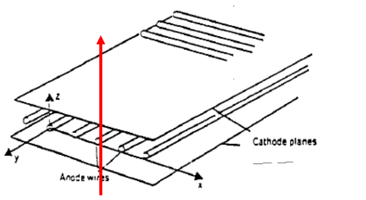
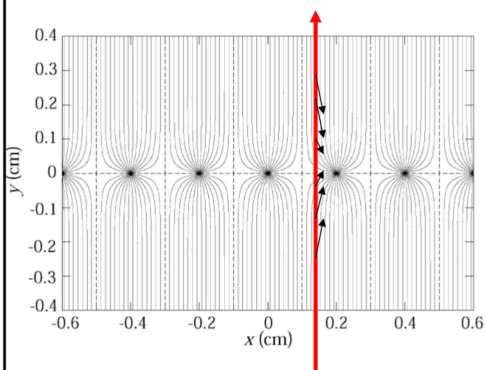


Abbildung 2.27: *Vieldrahtproportionalkammer.*



In order to eliminate the left/right ambiguities:

Shift two wire chambers by half the wire pitch.

For second coordinate:

→Another chamber at 90⁰ relative rotation

→Signal propagation to the two ends of the wire:

Pulse height measurement on both ends of the wire. Because of resisitvity of the wire, both ends see different charge)

→Segmenting of the cathode into strips or pads:

The movement of the charges induces a signal on the wire AND on the cathode. By segmentation of the cathode plane and charge interpolation, resolutions of 50μm can be achieved.

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Principle of Signal Induction by Moving Charges

A point charge q at a distance z_0

Above a grounded metal plate 'induces' a surface charge.

The total induced charge on the surface is –q.

Different positions of the charge result in different charge distributions.

The total induced charge stays –q.

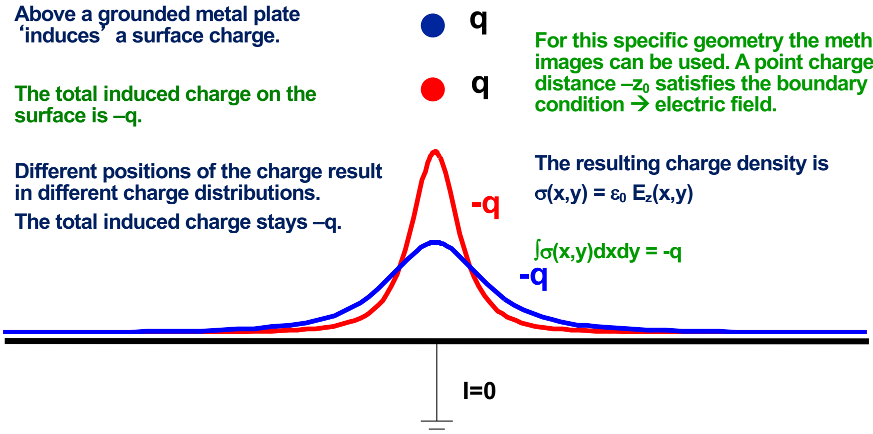
The electric field of the charge must be calculated with the boundary condition that the potential φ=0 at z=0.

For this specific geometry the method of images can be used. A point charge –q at distance $-z_0$ satisfies the boundary condition → electric field.

The resulting charge density is

$\sigma(x,y) = \varepsilon_0 E_z(x,y)$

$\int \sigma(x,y)dxdy = -q$



$$E_z(x,y) = -\frac{q z_0}{2\pi\varepsilon_0(x^2+y^2+z_0^2)^{\frac{3}{2}}} \qquad E_x = E_y = 0 \qquad \sigma(x,y) = \varepsilon_0 E_z(x,y) \qquad Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sigma(x,y)dxdy = -q$$

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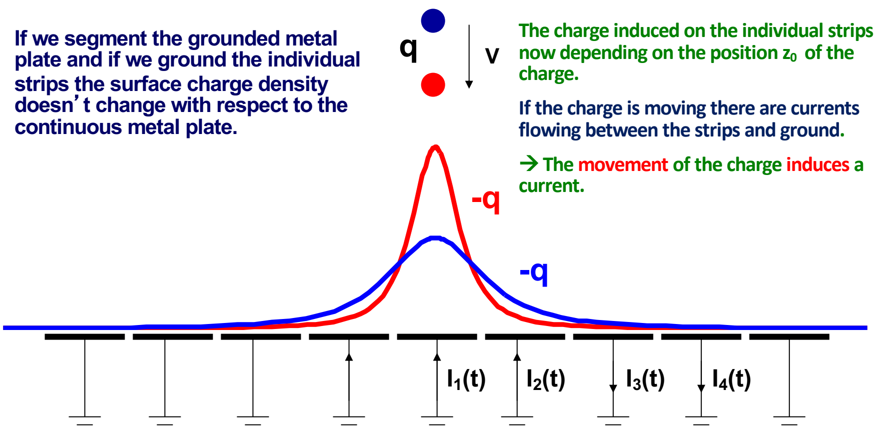
Principle of Signal Induction by Moving Charges

If we segment the grounded metal plate and if we ground the individual strips the surface charge density doesn't change with respect to the continuous metal plate.

The charge induced on the individual strips is now depending on the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.



$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2}\sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right)$$

$$z_0(t) = z_0 - vt$$

$$I_1^{ind}(t) = -\frac{d}{dt}Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0}\frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2+w^2]}v$$

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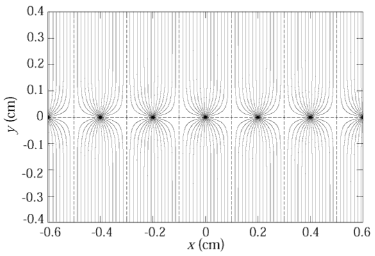
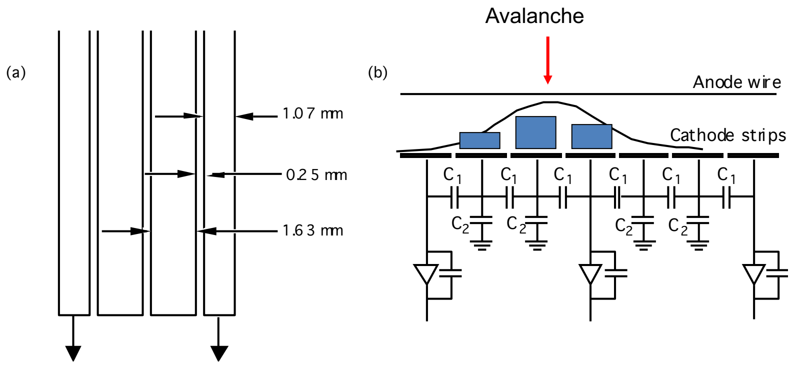
Multi Wire Proportional Chamber



Cathode strip:

Width (1σ) of the charge distribution ≈ distance between Wires and cathode plane.

'Center of gravity' defines the particle trajectory.



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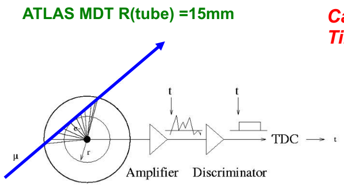
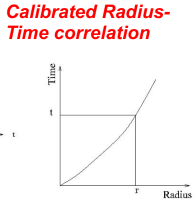
Drift Tube



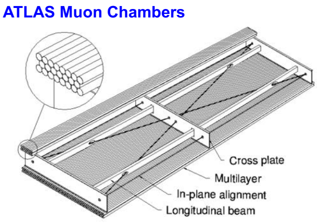


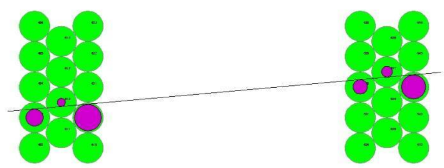
Primary electrons are drifting to the wire.

Electron avalanche at the wire.

The measured drift time is converted to a radius by a (calibrated) radius-time correlation.

Many of these circles define the particle track.





ATLAS MDTs, 80μm per tube

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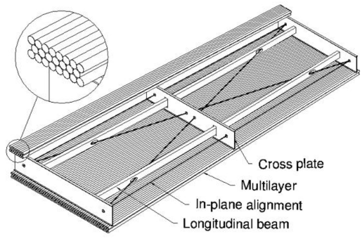
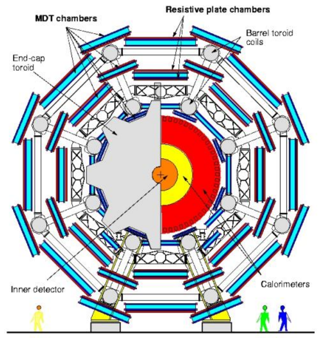
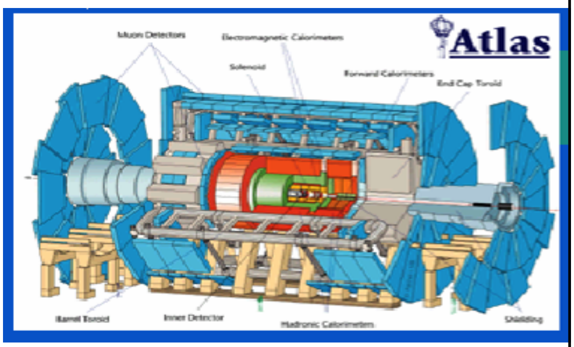
Drift Tube

Atlas Muon Spectrometer, 44m long, from r=5 to11m.
1200 Chambers
6 layers of 3cm tubes per chamber.
Length of the chambers 1-6m !
Position resolution: 80μm/tube, <50μm/chamber (3 bar)
Maximum drift time ≈700ns
Gas Ar/CO_2 93/7







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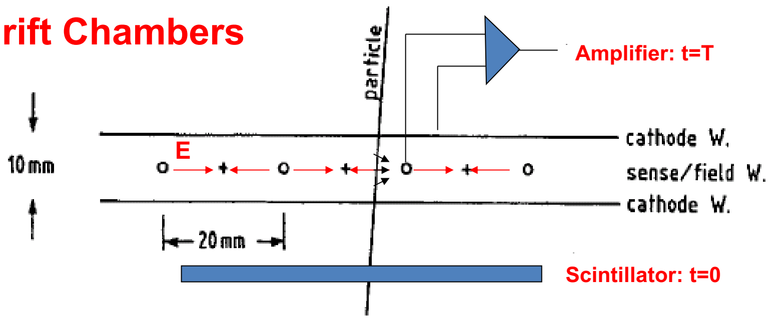
Drift Chambers



In an alternating sequence of wires with different potentials one finds an electric field between the 'sense wires' and 'field wires'.

The electrons are moving to the sense wires and produce an avalanche which induces a signal that is read out by electronics.

The time between the passage of the particle and the arrival of the electrons at the wire is measured.

The drift time T is a measure of the position of the particle !

By measuring the drift time, the wire distance can be increased (compared to the Multi Wire Proportional Chamber) → save electronics channels !

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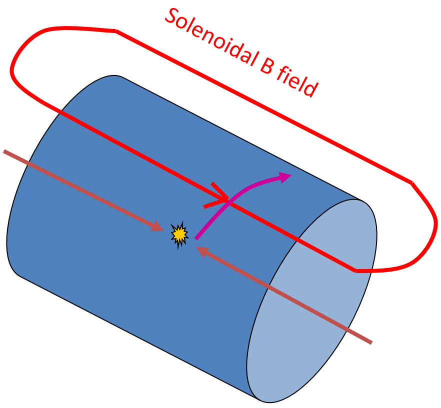
Drift Chambers

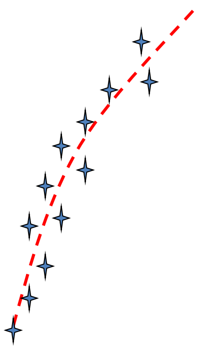


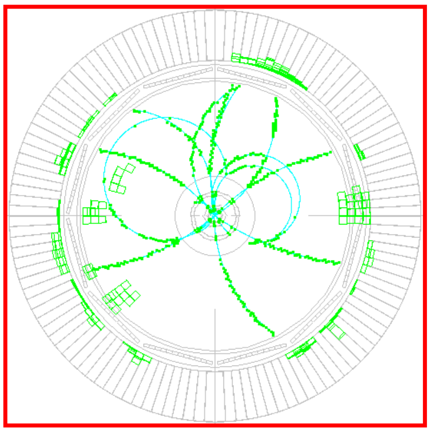
40,000 wires in BaBar drift Chamber with B field parallel to beam axis

35

Drift Chambers

Pattern Recognition to find a “road” of hits





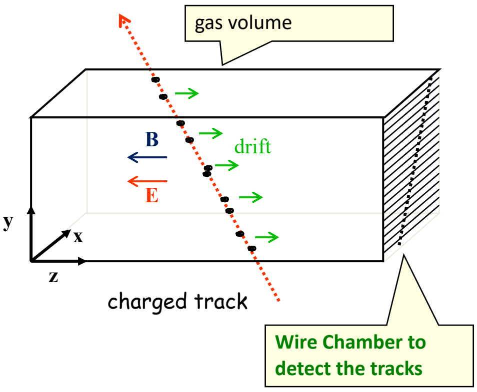
χ^2 fit to helix with correction for ***dE/dx to measure momentum***. Precision of 80 microns achievable

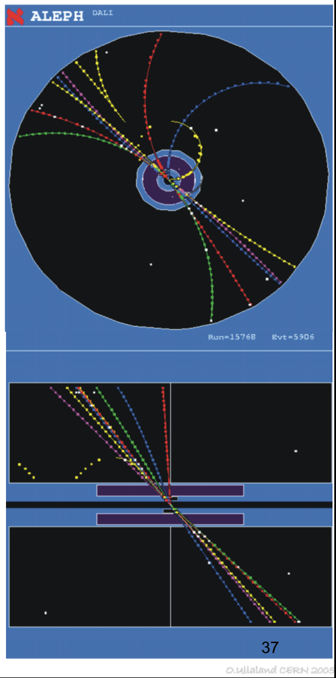
36

Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect:

Drift Fields 100-400V/cm. Drift times 10-100 μs.
Distance up to 2.5m !





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Summary on Gas Detectors

Wire chambers that can track up to MHz/cm^2 of particles

While silicon trackers currently outperform wire chambers close to the interaction regions, wire chambers are perfectly suited for the large detector areas at outer radii.

Gas detectors can be simulated very accurately due to excellent simulation programs.

The Time Projection Chamber – if the rate allows it's use – is unbeatable in terms of low material budget and channel economy. There is no reason for replacing a TPC with a silicon tracker.

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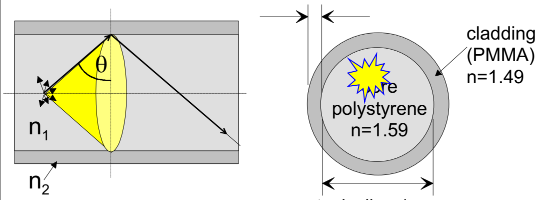
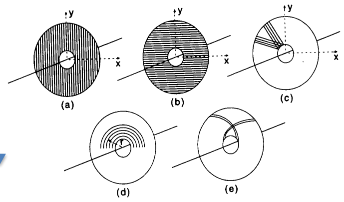
Fiber Tracking

Using scintillating fibers

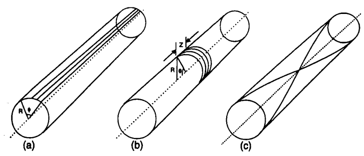
Light transport by total internal reflection



Planar geometries
(end cap)



Circular geometries
(barrel)



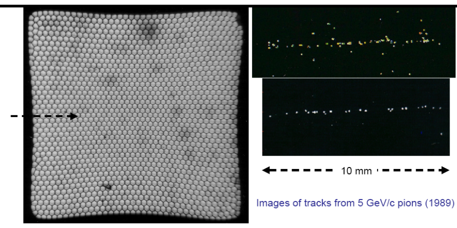
High geometrical flexibility

Fine granularity

Low mass

Fast response (ns)

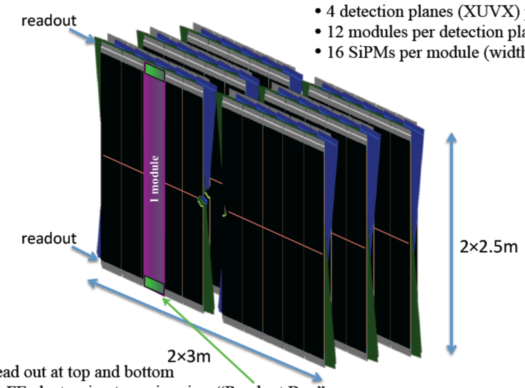
39

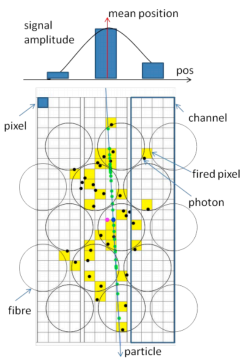


Images of tracks from 5 GeV/c pions (1989)

SciFi tracker stations layout

- 3 stations
- 4 detection planes (XUVX) per station
- 12 modules per detection plane
- 16 SiPMs per module (width ~530mm)





- Fibers read out at top and bottom
- SiPMs + FE electronics + services in a "Readout Box"

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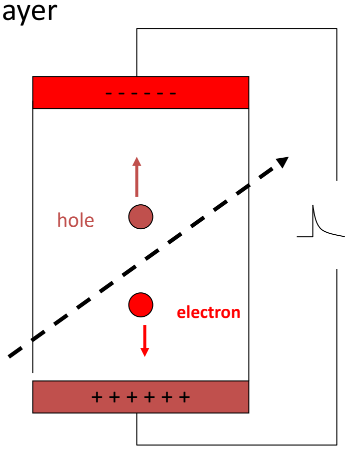
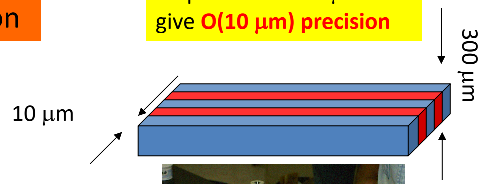
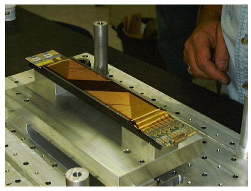
Tracking with Silicon Detectors

Ionizing particle creates electron/hole pair in the depletion layer



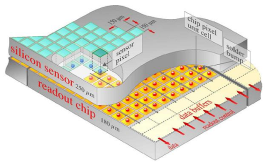
Detectors constructed of strips of width 10 μm to give **O(10 μm) precision**





Pixel detector

Typical size 50 x 200 μm.



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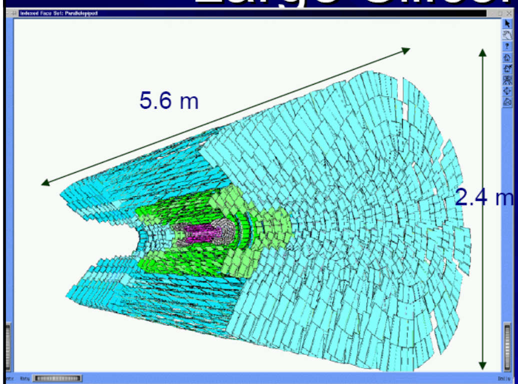
Large Silicon Systems



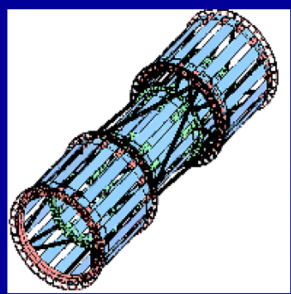
CMS tracker (~2007)

12000 modules

~ 445 m² silicon area

~ 24,328 silicon wafers

~ 60 M readout channels



CDF SVX IIa (2001-)

~ 11m² silicon area

~ 750 000 readout channels

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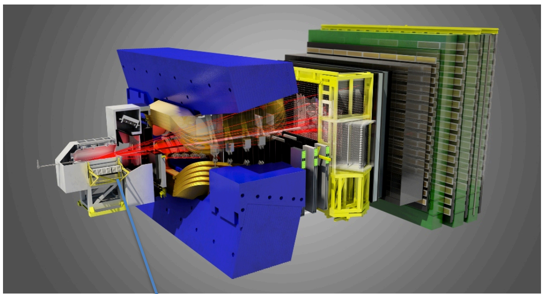
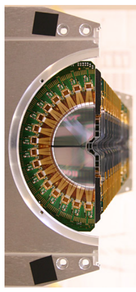
B) Vertexing

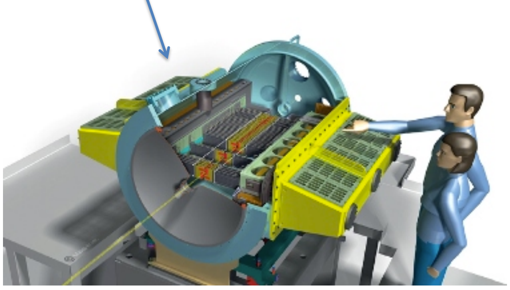
with

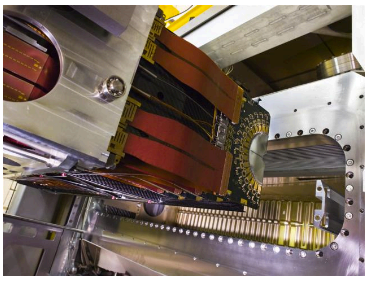
solid Detectors

The LHCB vertex locator (VELO)

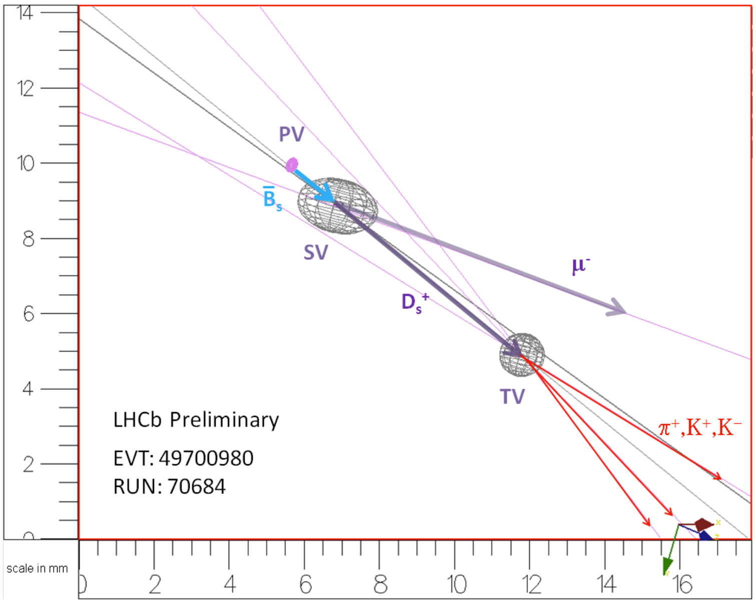








B. Vertex reconstruction with silicon detectors



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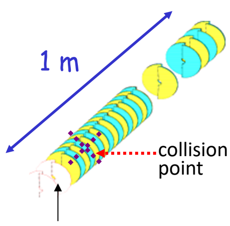
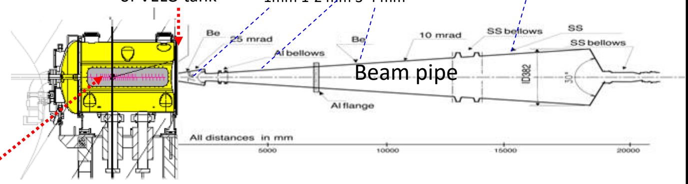
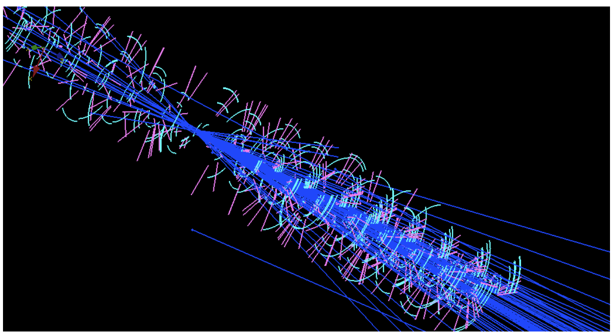
VErtex LOcator





(For Pile-up veto)



21 stations each with 2 modules of Silicon 300 μ-strip detectors that partially overlap, and as close as 5mm from the beam (retractile, 172K channels)

r-ϕgeometry variable pitch [r (40-102μ);ϕ(36-97μ)]

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Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement (LHCb) but also for momentum spectroscopy over large areas (CMS) .

Technology is improving rapidly due to rapid Silicon development for electronics industry.

Typical numbers where detectors start to strongly degrade are 10^{14}-10^{15} hadron/cm^2.

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C) PARTICLE IDENTIFICATION

- Measure dE/dx (example: ionization in gas)
- Measure Cherenkov light
- (Combine information of different detectors)

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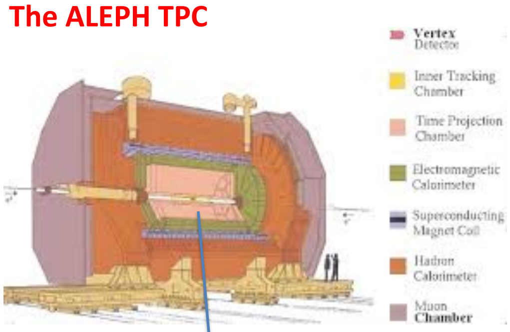
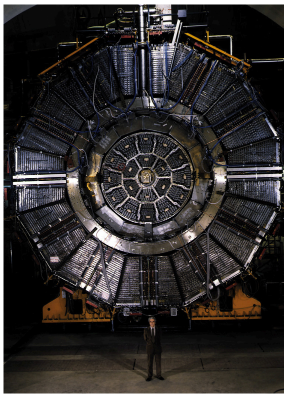
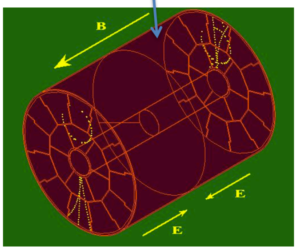
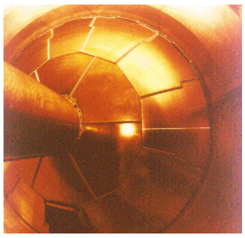
Example of dE/dx measurement: The ALEPH TPC









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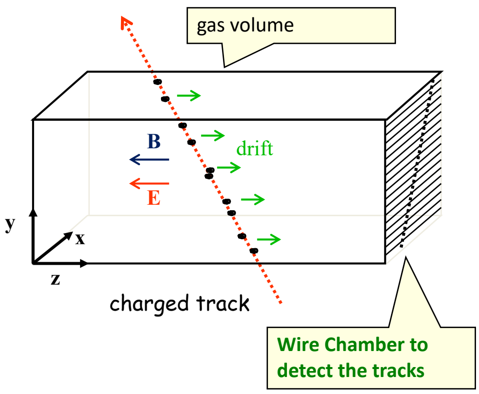
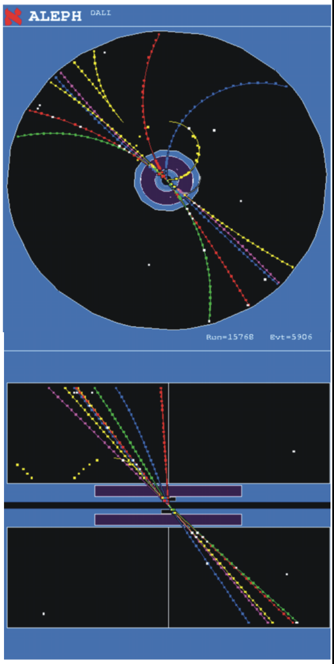
Time Projection Chamber (TPC):

Gas volume with parallel E and B Field.
B for momentum measurement. Positive effect:

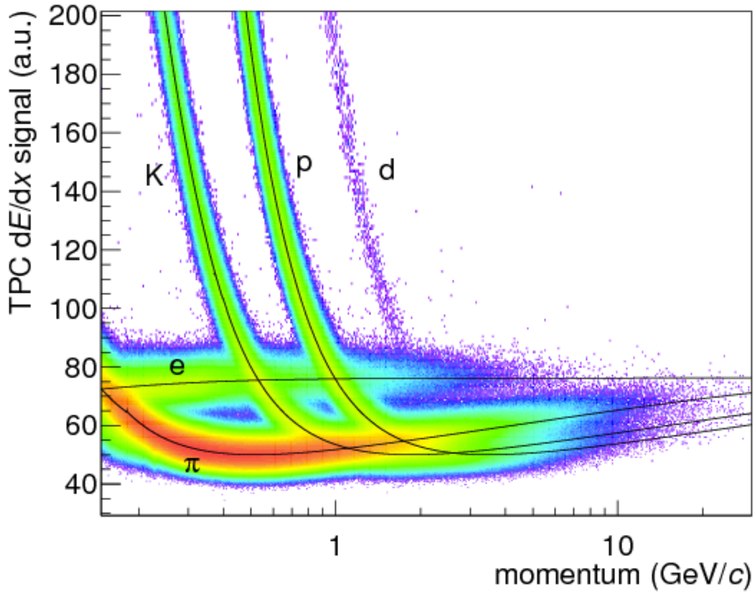
Drift Fields 100-400V/cm. Drift times 10-100 μs.
Distance up to 2.5m !





Measure dE/dx (= collected charge) on the wire chamber

50



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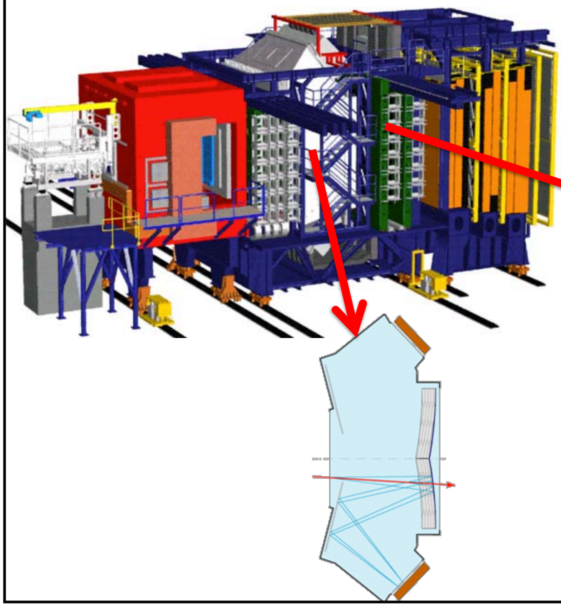
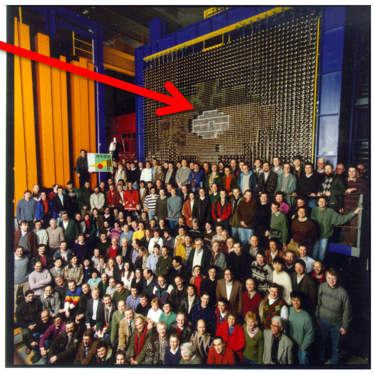
Example of a Cherenkov detector: the RICH of HERA-B (RICH: Ring Imaging Cherenkov)





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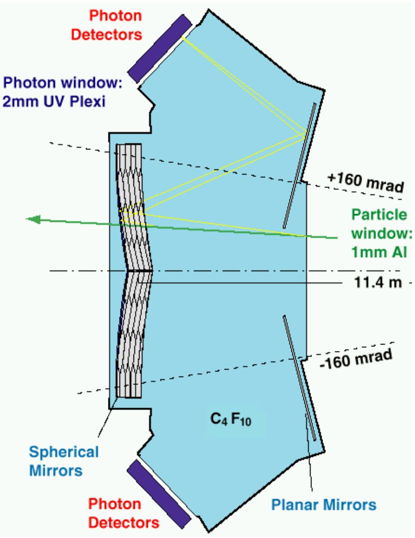
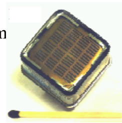
HERA-B Rich



- Vessel
  - 100 m^3 stainless steel tank
  - gas: C4F10, n-1=1.35x10^{-3}
  - 35g/ring(beta=1)
  - q $_c$(beta=1)=52 mrad (angle error 0.8 mrad)
  - p 1.7 Gev, K 9.6 GeV, p 18 GeV
- Mirrors
  - Spherical: 80 full or partial hexagons; 7mm thick Pyrex,

    coating 200nm Al, 30 nm MgF_2, radius 11.4 m, 24 m^2 area
  - planar: 24
  - alignment: done by surveying (autoreflection), movement by motor
- Focal plane
  - photon detection: Photomultipliers Hamam R5900 with light collection telescopes



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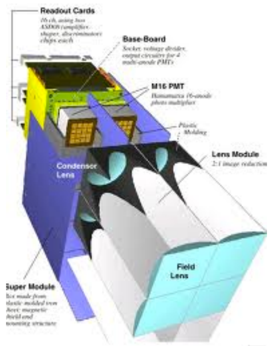
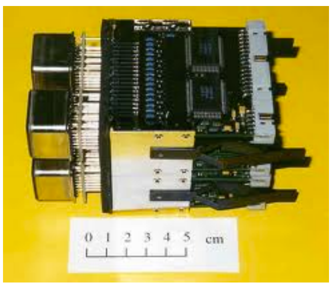
HERA-B RICH





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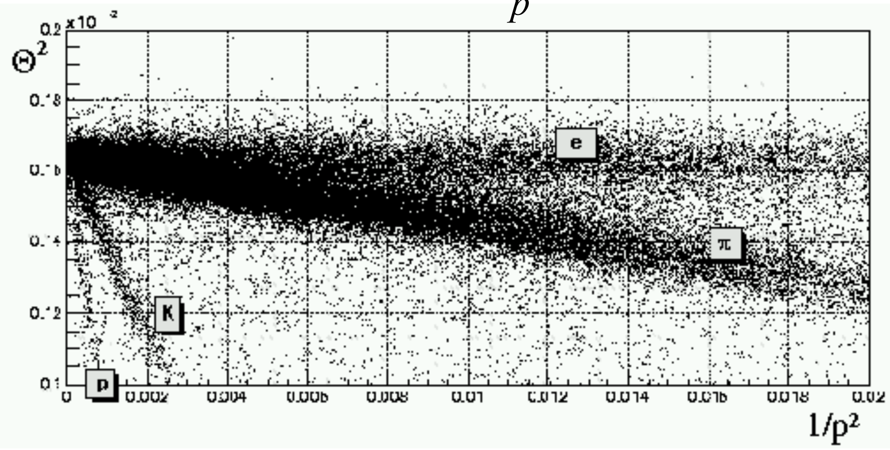
Particle ID:

$$\theta_c^2 = \theta_0^2 - \frac{m^2}{p^2}$$



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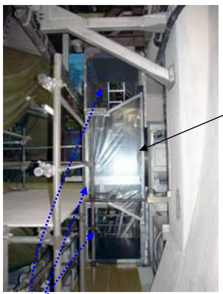
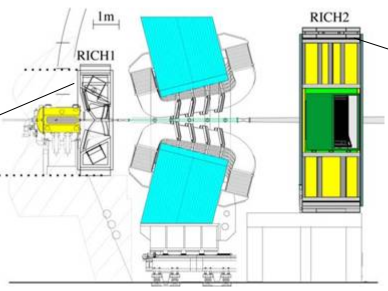
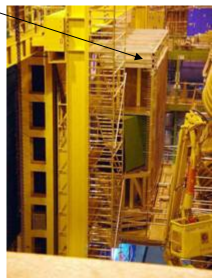
LHCb Ring Image Cherenkov (RICH)

RICH1:
(Aerogel&C_4F_{10}, 25-300 mrad)

RICH2:
(CF4, 15-120 mrad)







Installed:
Magnetic shield
Gas enclosure
Seal-to-VELO
Beam pipe

Photon detector:
HPD

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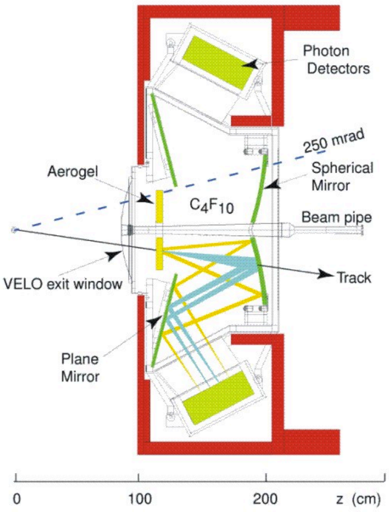
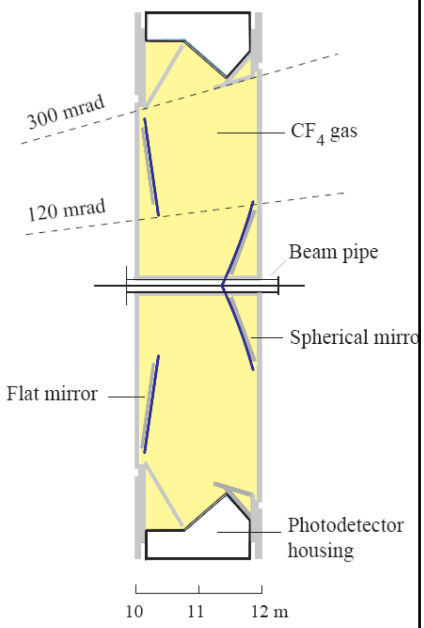
LHCb RICH





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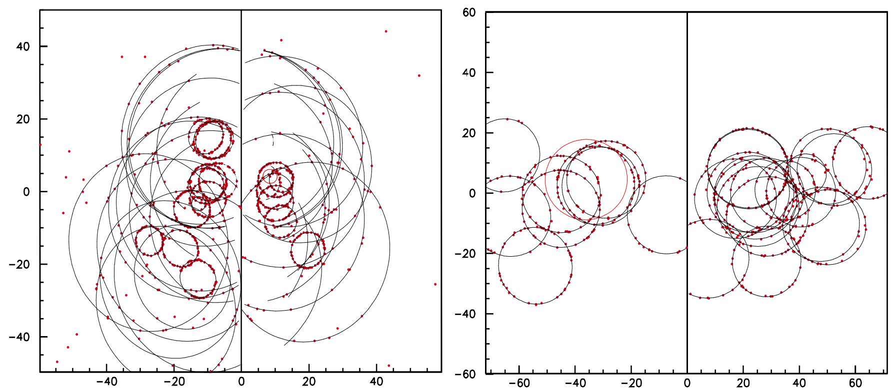
Reconstructed Cherenkov Rings



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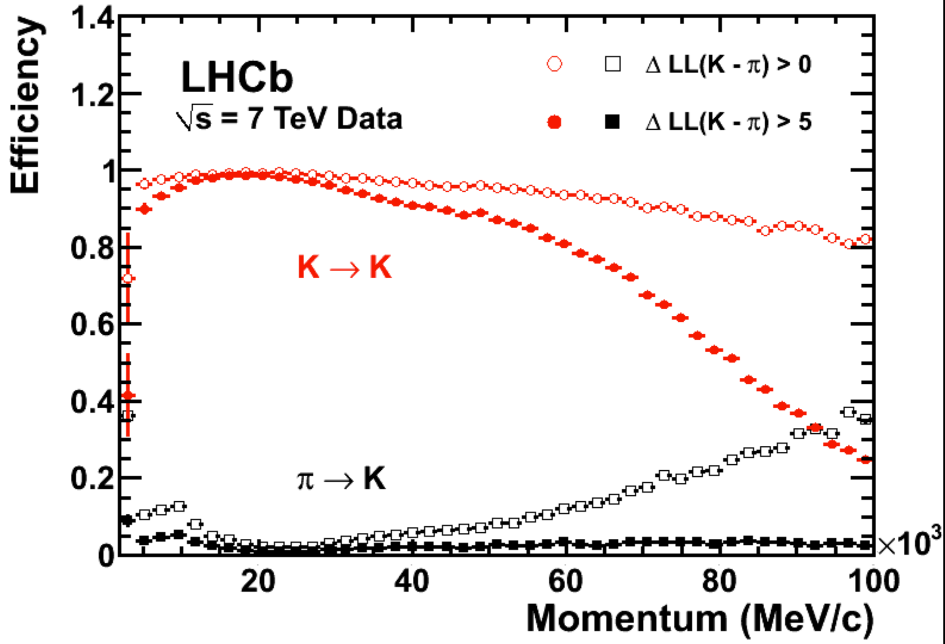
RICH performance



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D) Calorimetry

Energy Measurement by total Absorption of Particles

- **Electromagnetic calorimeter: measure the energy of electrons and photons**
- **Hadronic calorimeter: measure the energy of neutral and charged hadrons**

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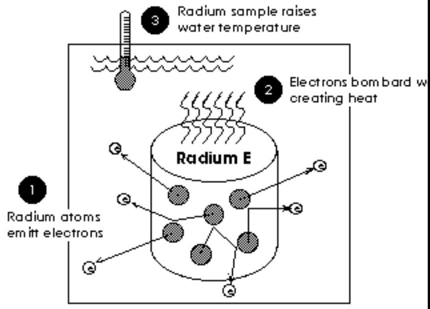
Calorimeter ?: Radium E experiment

(we do not measure T !!!)

In 1927, two physicists, C. D. Ellis and W. A. Wooster, set out to measure the energy given off by Radium E decaying into Polonium. The experiment was simple: place the most pure form or RaE available at the time into a calorimeter and measure the output.

Beta decay was well understood at the time: each RaE atom naturally decays into one electron and one proton.



Since the number of atoms in the sample is known, Ellis and Wooster only had to measure the heat given off by the Radium E sample to discover the amount of energy emitted in the process of decay.

From experimental results, they calculated that each RaE atom naturally emits 0.36 MeV: exactly equivalent to the energy of one electron.

(Note: 1 eV = 1.6×10^{-19} Joules = 1.8×10^{-33} grams)

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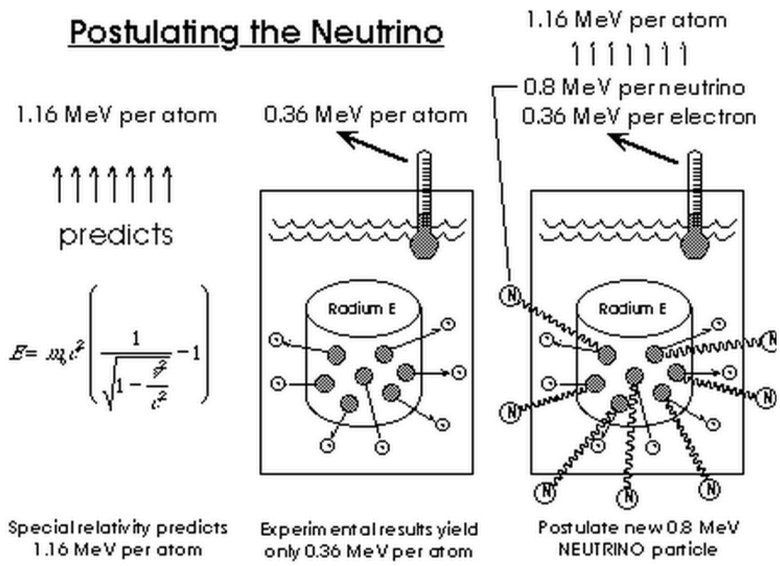
E=mc^2



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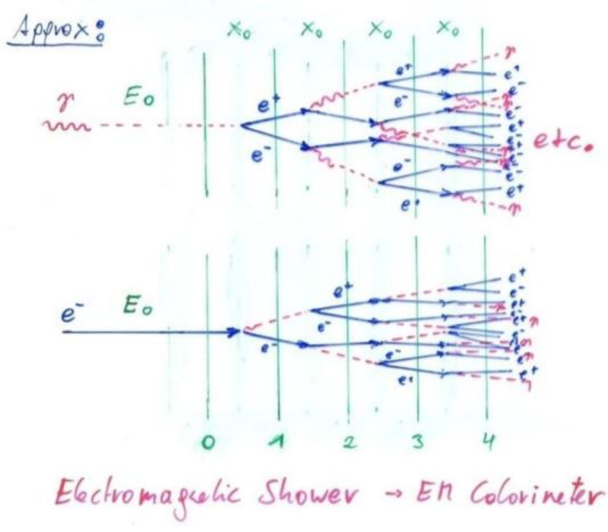
Bremsstrahlung + Pair Production → EM Shower



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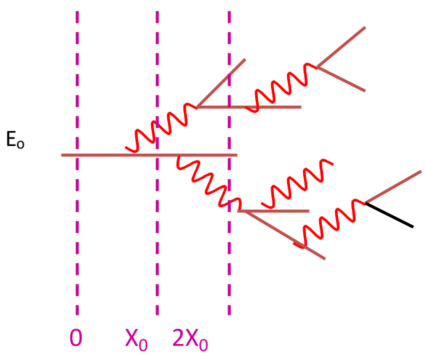
Electromagnetic Showers

Number of particle after
t radiation lengths= N(t)



$$N(t) = 2^t = e^{t \ln 2}$$

$$N(t_{\max}) = \frac{E_0}{E_c} = 2^{t_{\max}}$$

$$t_{\max} \propto \ln(E_0)$$

The total track length of particles (in units of Xo)

$$L = \frac{E_0}{E_c}$$

How to measure the signal of the shower?

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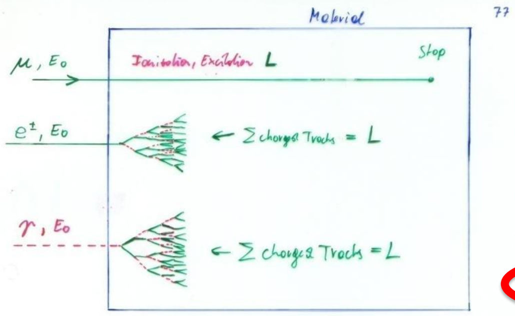
EM Calorimetry (I)



If N is the total Number of e^-, I^+ pairs or photons, or $N = c_1 E_0$:

$\Delta N = \sqrt{N}$ (Poisson Statistics)

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{a}{\sqrt{E}} \rightarrow \text{Resolution}$$

The $e^{\pm}$ in the Calorimeter ionize and excite the Material

Ionization: e^-, I^+ pairs in the Material

Excitation: Photons in the Material

Measuring the total Number of e^-, I^+ pairs or the total Number of Photons gives the particle Energy.

Calorimeter: Δ E/E α 1/ √ E

Momentum Spectrometer: Δp/p α p

Energy measurement improves with higher particle energies – LHC !

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EM Calorimetry (II)

Radiation Length X_0 and Moliere Radius are two key parameters for choice of calorimeter materials

Approximate longitudinal shower development

$N(n) = 2^n$ ..... Number of particles $(e^{\pm}, \gamma)$ after $n X_0$

$E(n) = \frac{E_0}{2^n}$ .... Average Energy of particles after $n X_0$

Shower stops if $E(n) = E_{critical}$

$\rightarrow n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c} \rightarrow$ Shower length rises with $\ln E_0$

Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadonic showers in a similar fashion to the EM cascade
→Hadronic calorimetry

Approximate transverse shower development

The transverse Shower Dimension is mainly related to the Multiple scattering of the low Energy Electrons.

$$\theta_0 \sim \frac{21\,[\text{MeV}]}{\beta p[\frac{\text{MeV}}{c}]} z_1 \cdot \sqrt{\frac{x}{X_0}}$$

Electrons E_c, $E \sim p \cdot c$

$$\theta_0 \sim \frac{21\,[\text{MeV}]}{\beta E_c\,[\text{MeV}]} \cdot z_1 \cdot \sqrt{\frac{x}{X_0}} \qquad z_1 = 1,\ \beta \sim 1$$

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

$$\theta_0 = 0.0344 \cdot Z \cdot \sqrt{\frac{x}{X_0}}$$

Moliere Radius ρ_m = lateral Shower Radius after $1 X_0$:

$$\rho_m \approx 0.0344 \cdot Z \cdot X_0$$

95% of Energy are in a Cylinder of $2\rho_m$ Radius.

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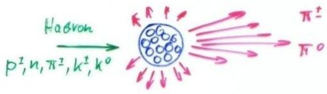
Hadronic Calorimetry



Strong Interaction

Approximate Energy Distribution

~50%	~20%	~30%
π^+, π^- $\pi^0 \to \gamma\gamma$	Nuclear Excitation 5-30 MeV p, n, γ	Slow Nucleons

π^+, π^- $\pi^+, \pi^-, \pi^0 \to \gamma\gamma$

Hadron kaskade

$\pi^0 \to \gamma\gamma \to$ Electromagnetic Component

In Hadronic Cascades the Longitudinal Shower is given by the Absorption Length λ_a $I \sim e^{-\frac{x}{\lambda_a}}$

In typical Detector Materials λ_a is much longer than X_0

$$\lambda \sim \frac{1}{\rho} \cdot 35\, A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7.87	1.76 cm	~17 cm
Pb	11.35	0.56 cm	~17 cm

Energy Resolution:

- A large Fraction of the Energy 'disappears' into
  - Binding Energy of emitted Nucleons
  - $\pi \to \mu + \nu$ which are not absorbed
- π^0's Decaying into $\gamma\gamma$ start an EM Cascade ($\tau \sim 10^{-17}$ s)

— Energy Resolution is worse than for EM Calorimeters

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Hadron Calorimeters are Large because lambda is large

ALEPH

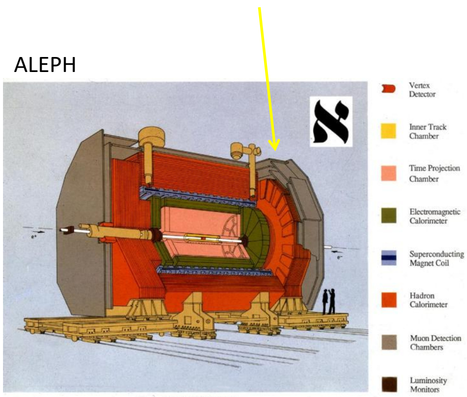
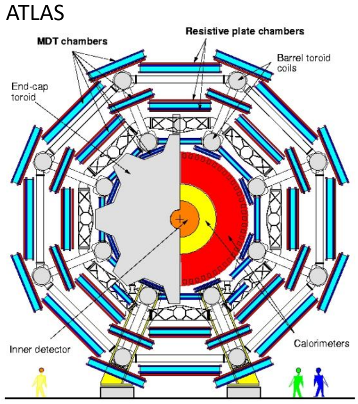


Fig. 1 - The ALEPH Detector

Hadron Calorimeters are large and heavy because the hadronic interaction length, the 'strong interaction equivalent' to the EM radiation length X_0, is large (5-10 times larger than X_0)

ATLAS



Because part of the energy is 'invisible' (nuclear excitation, slow nucleons), the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/Sqrt[E(GeV)] .

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Calorimetry

Calorimeters are attractive in our field for various reasons:

the calorimeter energy resolution improves as 1/Sqrt(E)

calorimeters are sensitive to all types of particles, charged and neutral

Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are cost effective because the shower length increases only logarithmically with energy

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Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

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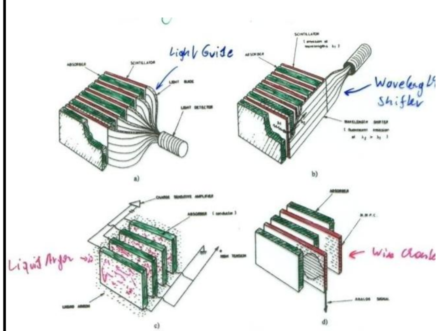
Sampling Calorimeters



Alternation of "passive" absorber plates and "active" readout sections

Advantages:
- optimum choice of Absorber Material
- optimum choice of Signal Readout
- Compact and cheap Construction

"passive": Pb, Fe ....

"active": Scintillator (Signal → Photons)
Noble Liquid, e.g. Ar (Signal → e^-, I^+)
Wire Chambers (Signal → e^-, I^+)

Energy resolution of sampling calorimeters is in general worse than that of homogeneous calorimeters, owing to the sampling fluctuations – the fluctuation of ratio of energy deposited in the active and passive material.

The resolution is typically in the range 5-20%/Sqrt[E(GeV)] for EM calorimeters. On the other hand they are relatively easy to segment longitudinally and laterally and therefore they usually offer better space resolution and particle identification than homogeneous calorimeters.

The active medium can be scintillators (organic), solid state detectors, gas detectors or liquids.

Sampling Fraction = Energy deposited in Active/Energy deposited in passive material.

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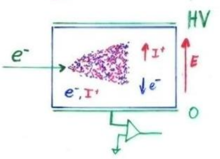
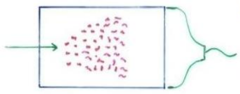
Homogeneous Calorimeters

The measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



Collecting the produced Charge



Measuring the Photons produced by the collision of the $e^\pm$ with Atom Electrons of the material.

Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

Measure charge or light

Liquid Nobel Gases (Nobel Liquids)

Scintillating Crystals, Plastic Scintillators

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Crystals for Homogeneous EM Calorimetry

	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5
		Barbar@PEPII, 10ms interaction rate, good light yield, good S/N	KTeV@Tevatron, High rate, Good resolution	L3@LEP, 25us bunch crossing, Low radiation dose	CMS@LHC, 25ns bunch crossing, high radiation dose

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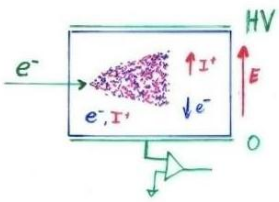
Noble Liquids for Homogeneous EM Calorimetry

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3



When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters (see later).

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Detector Systems

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Towards a general purpose particle detector

A. **Reconstruct momentum of charged particles**
   - Need of magnetic field
   - Low material budget to avoid large multiple scattering and lost of energy
   - Measure ionization effects on gas or solid devices
B. **Reconstruct decay vertices**
   - Very low material budget to avoid large multiple scattering and lost of energy
   - Measure ionization effects on solid devices with very high position resolution
C. **Find the type of particle**
   - Measure dE/dx (example: ionization in gas)
   - Measure Cherenkov light
   - Combine information of different detectors
D. **Energy measurement by total Absorption of Particles (CALORIMERTER)**
   - **ELECTROMAGNETIC calorimeter: energy measurement of electrons and photons**
     Measure energy lost in a dense material (use gas/scintillator to measure a fraction of the ionization energy lost)
   - **HADRONIC calorimeter: energy measurement of neutral and charged hadrons**
     Measure energy lost (including strong interactions with nucleus) in a dense material (use gas/scintillator to measure a fraction of the ionization energy lost)

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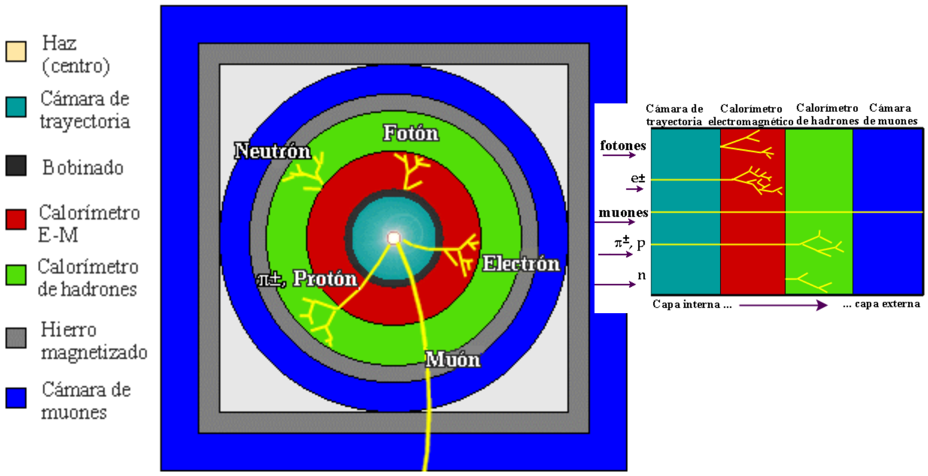
Detectors

Sección de un detector mostrando las trayectorias de las partículas



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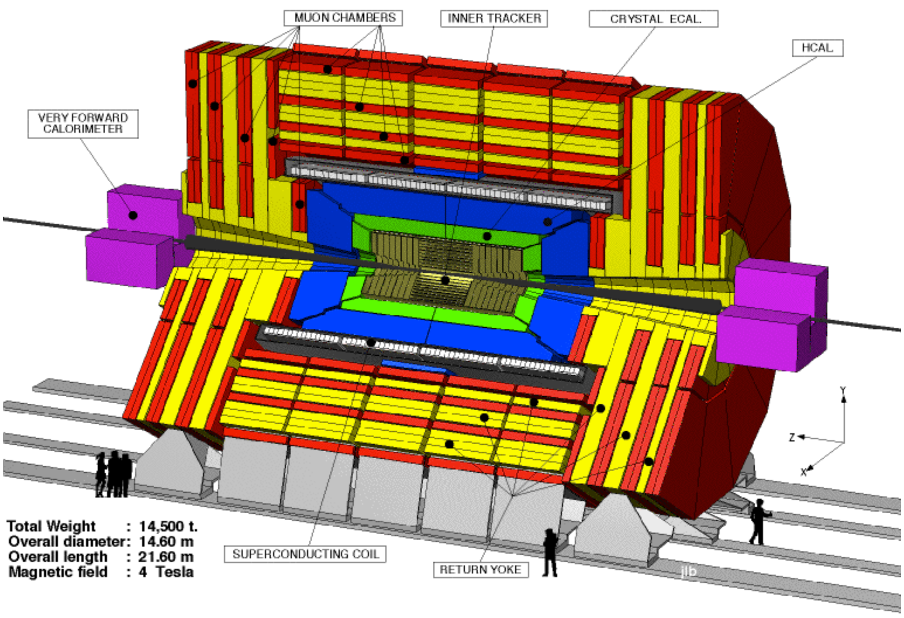
The CMS detector



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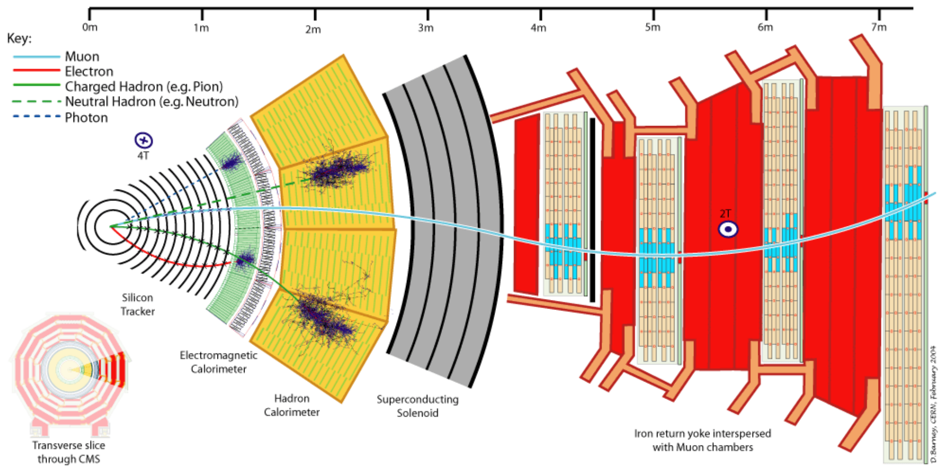

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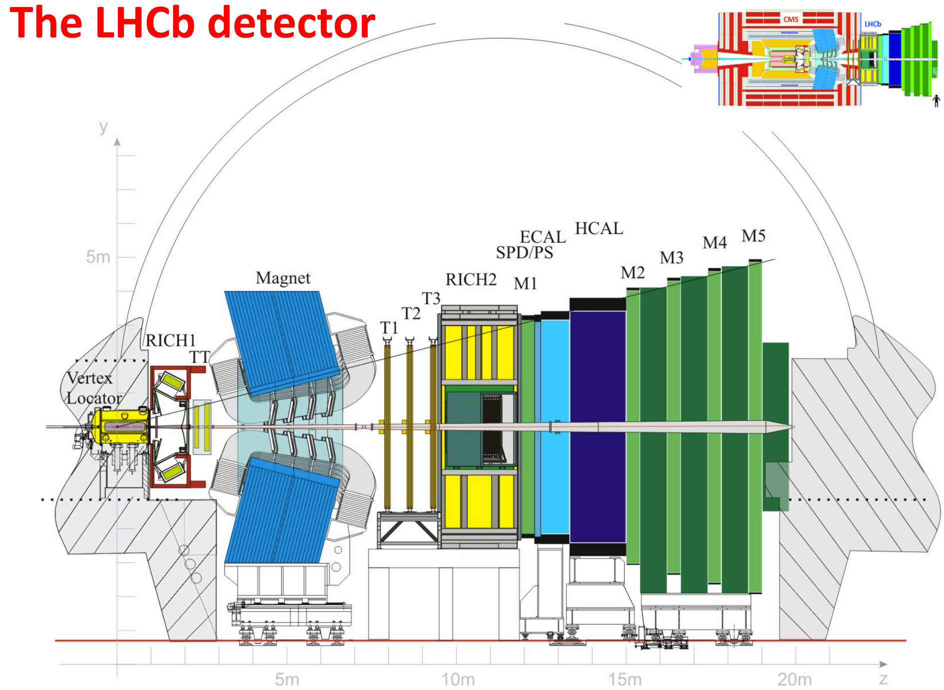
The LHCb detector



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