Semiconductor detectors

An introduction to
semiconductor detector physics
as applied to particle physics

Contents

4 lectures – can’t cover much of a huge field

- Introduction
- Fundamentals of operation
- The micro-strip detector
- Radiation hardness issues

Lecture 1 - Introduction

- What do we want to do
- Past, present and near future
- Why use semiconductor detectors

What we want to do - Just PPE

- Track particles without disturbing them
- Determined position of primary interaction vertex and secondary decays
  - Superb position resolution
    - Highly segmented ⇒ high resolution
  - Large signal
    - Small amount of energy to crate signal quanta
  - Thin
    - Close to interaction point
  - Low mass
    - Minimise multiple scattering
      - Detector
      - Readout
      - Cooling / support

Ages of silicon - the birth

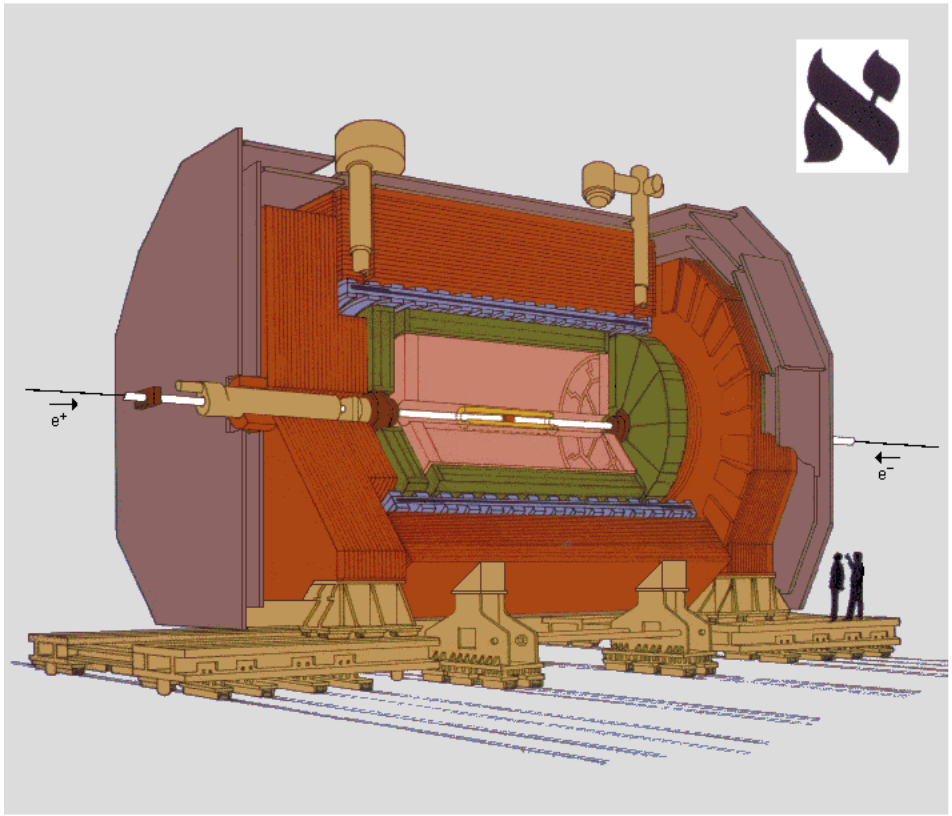
- J. Kemmer
  - Fixed target experiment with a planar diode*
  - Later strip devices -1980
  - Larger devices with huge ancillary components

* J. Kemmer: “Fabrication of a low-noise silicon radiation detector by the planar process”, NIM A169, pp499, 1980

Ages of Silicon - vertex detectors

- LEP and SLAC
  - Almost 4π coverage
  - ASIC's at end of ladders
  - Minimise the mass inside tracking volume
  - Minimise the mass between interaction point and detectors
  - Minimise the distance between interaction point and the detectors
- Enabled heavy flavour physics i.e. short lived particles

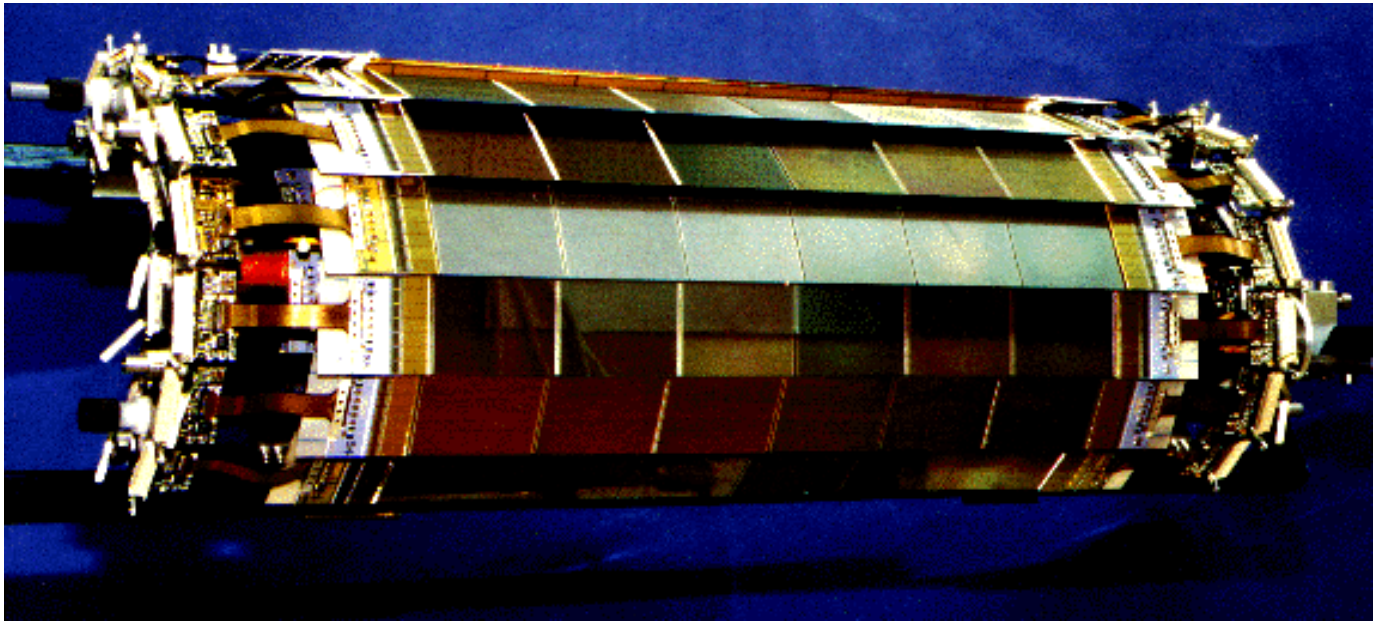
ALEPH



The ALEPH Detector

- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

ALPEH – VDET (the upgrade)

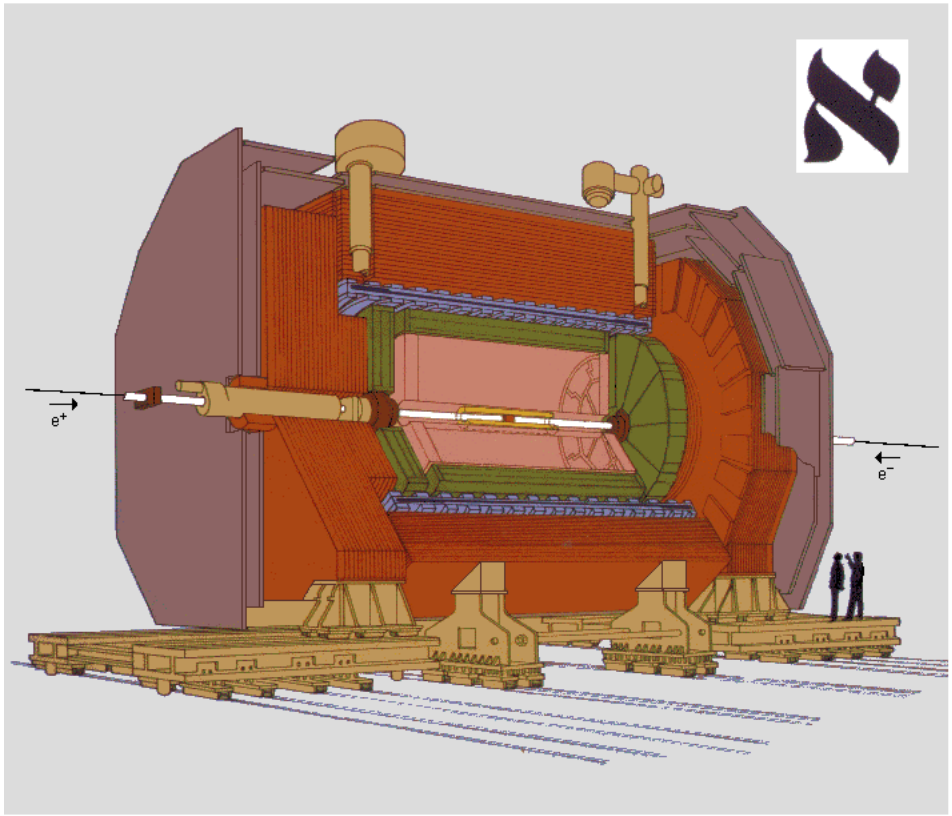


- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300μm Silicon wafers giving thickness of only $0.015X_0$
- Pitch
  - r-phi side: 25 μm, with R/O pitch of 50 μm
  - z side : 100 μm
- S/N rΦ = 28:1; z = 17:1
- $\sigma_{r\phi}$ = 12μm; σ_z = 14μm reduced due to multiple scattering to 20μm and 40μm respectively.

Ages of silicon - tracking paradigm

- CDF/D0 & LHC
  - Emphasis shifted to tracking + vertexing
  - Only possible as increased energy of particles
- Cover large area with many silicon layers
- Detector modules including ASIC's and services INSIDE the tracking volume
- Module size limited by electronic noise due to fast shaping time of electronics (bunch crossing rate determined)
  - Noise sources covered in later chapter, but limited by capacitance load "seen" by the front end amplifier, which is proportional to the length of the silicon detector strip

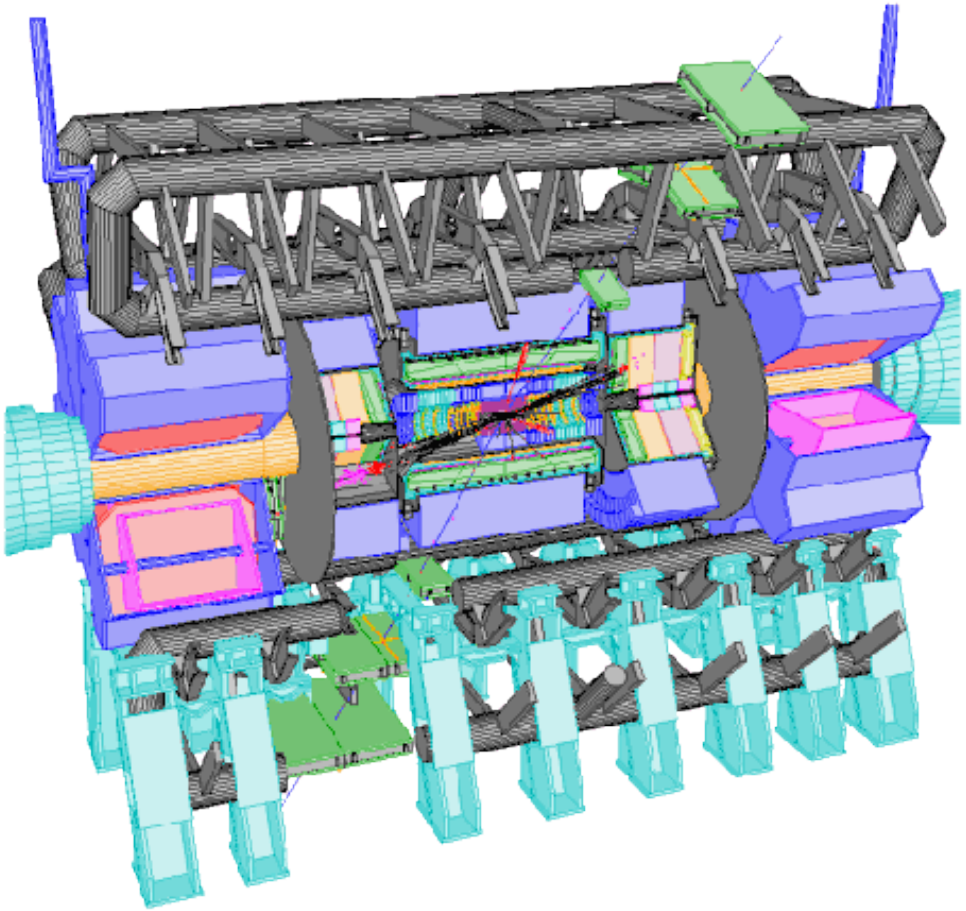
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The ALEPH Detector

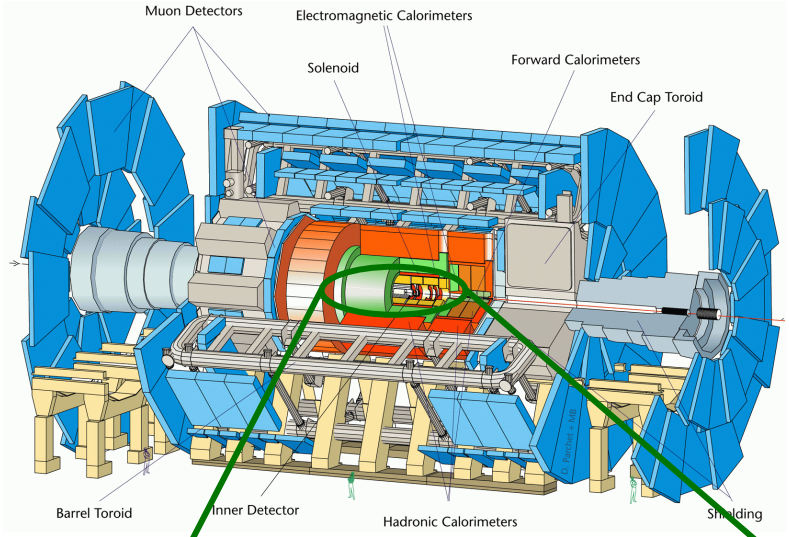
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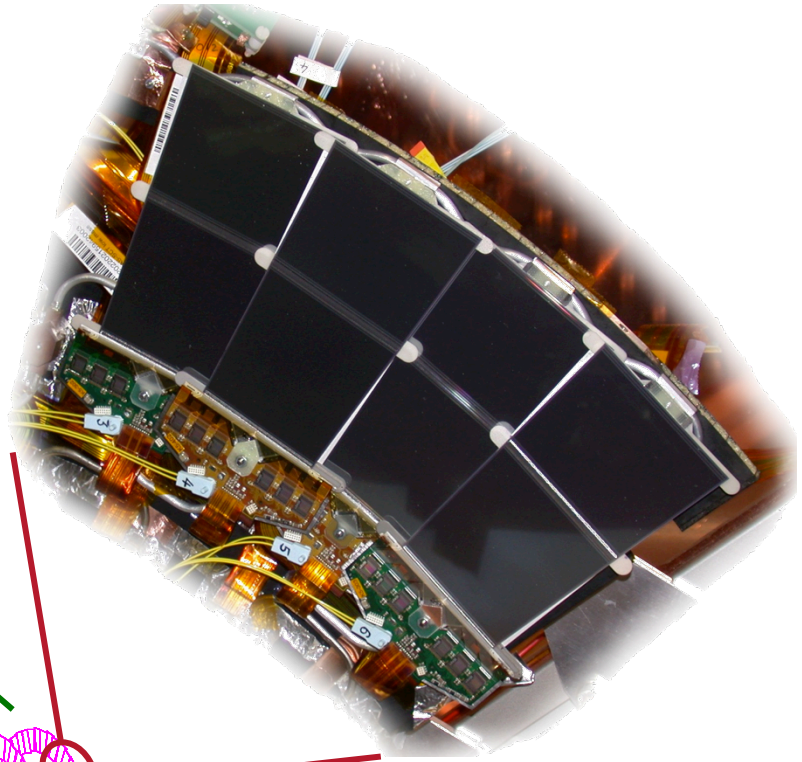
ATLAS

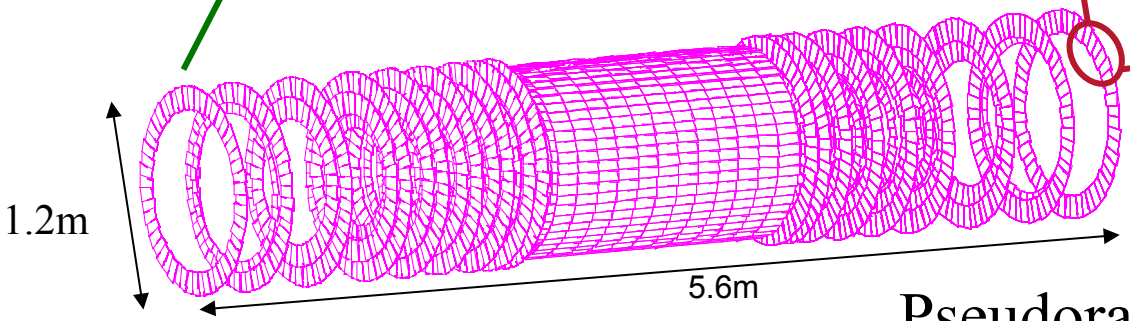


- A monster !
- ATLAS is mainly magnets and muon chambers and is 5 stories tall
- The inner tracking detector is a cylinder of ≈ 2m diameter and 6m long

Introduction

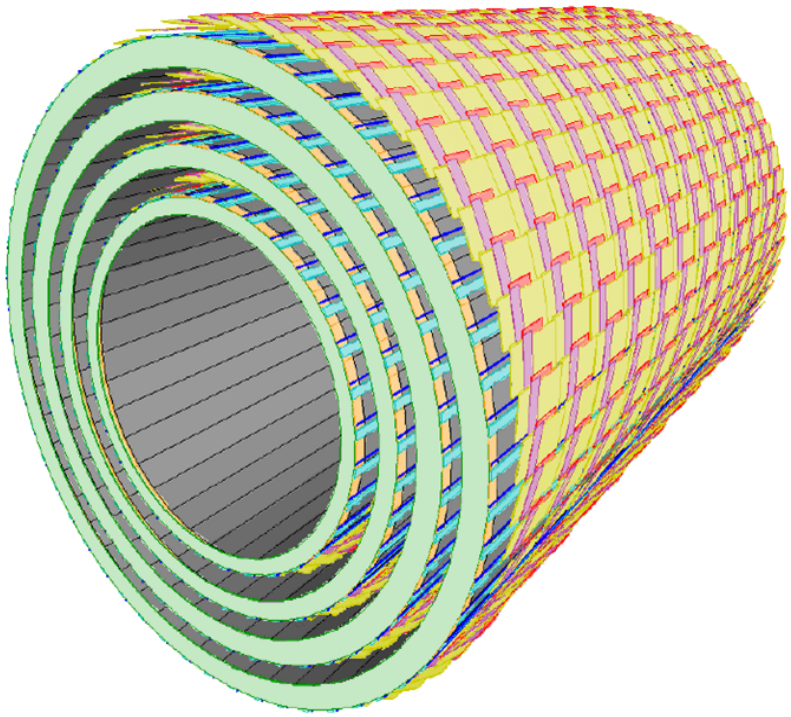






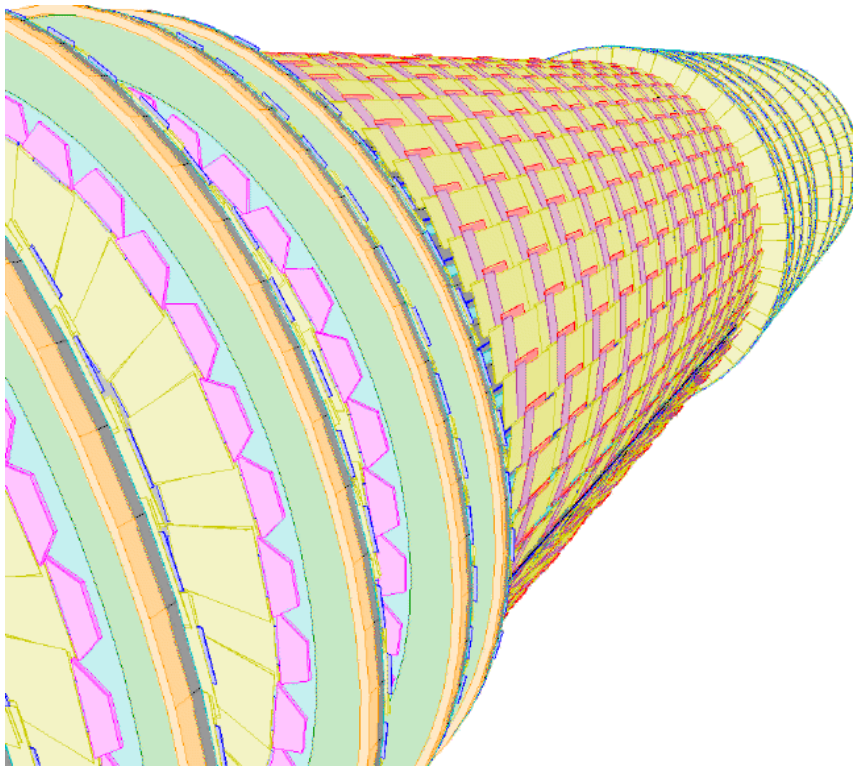
4 cylindrical barrels
9 disks per Endcap
Pseudorapidity coverage of ±2.5

ATLAS barrel



- 2112 Barrel modules mounted on 4 carbon fibre concentric Barrels, 12 in each row
- 1976 End-cap modules mounted on 9 disks at each end of the barrel region

Barrel and Endcaps



- Barrel modules are normal to the incident beam direction, centered on the interaction point
- Endcap modules are perpendicular to the beam direction as tracks from particles are now at a significant angle to the beam direction

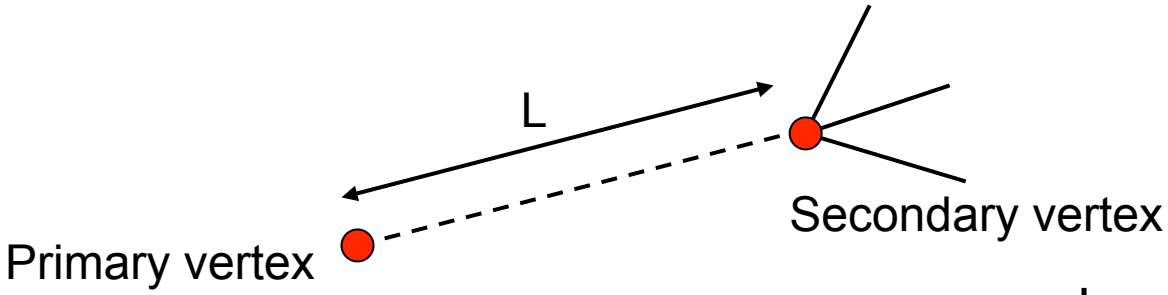
What is measured

- Measure space points
- Deduce
  - Vertex location
  - Decay lengths
  - Impact parameters

Signature of Heavy Flavours

Stable particles $\tau > 10^{-6}$ s		$c\tau$
n		2.66km
μ		658m
Very long lived particles $\tau > 10^{-10}$ s		
π, $K^{\pm}$, K_L^0	2.6×10^{-8}	7.8m
K_S^0, $E^{\pm}$, Δ^0	2.6×10^{-10}	7.9cm
Long lived particles $\tau > 10^{-13}$ s		
$\tau^{\pm}$	0.3×10^{-12}	91μm
B_d^0, B_s^0, Δ_b	1.2×10^{-12}	350μm
Short lived particles		
π^0, η^0	8.4×10^{-17}	0.025μm
ρ,ω	4×10^{-23}	$10^{-9}\mu$m!!

Decay lengths

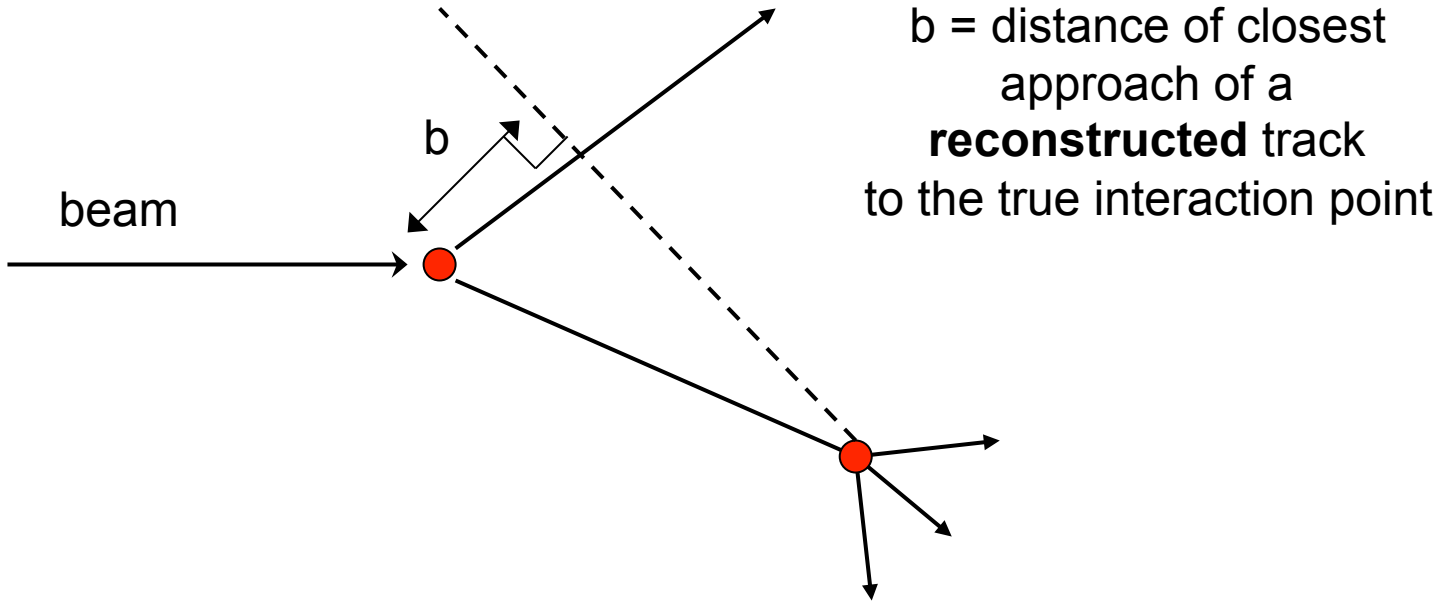


E.g. $B \rightarrow J/\Psi\ K_s^0$

$L = p/m\ c\ \tau$

- By measuring the decay length, L, and the momentum, p, the lifetime of the particle can be determined
- Need accuracy on both production and decay point

Impact parameter (b)



b = distance of closest approach of a **reconstructed** track to the true interaction point

Impact parameter

- Error in impact parameter for 2 precision measurements at R_1 and R_2 measured in two detector planes:

$$\sigma_b = a^2 + \left(\frac{b}{p}\right)^2 + c^2$$

- a=f(R_1 & R_2) and function of intrinsic resolution of vertex detector
- b due to multiple scattering in detector
- c due to detector alignment and stability

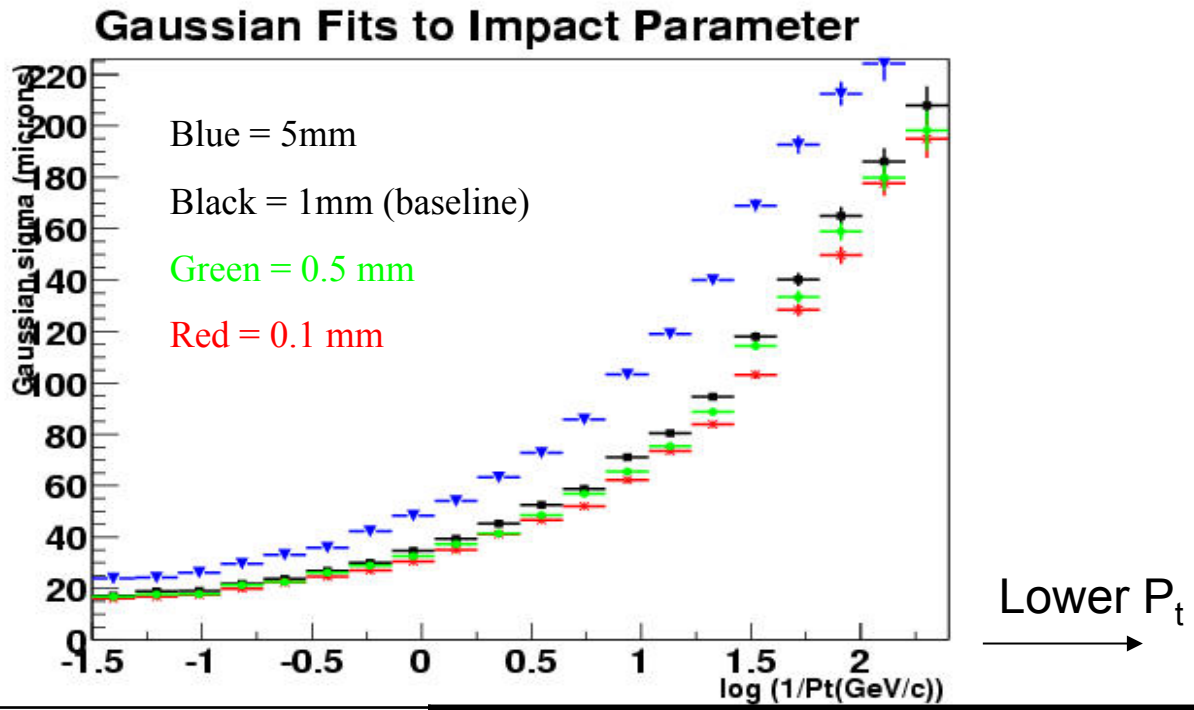
Impact parameter

- σ_b = f(vertex layers, distance from main vertex, spatial resolution of each detector, material before precision measurement, alignment, stability)

- Requirements for best measurement
  - Close as possible to interaction point
  - Maximum lever arm $R_2 - R_1$
  - Maximum number of space points
  - High spatial resolution of individual detector elements
  - Smallest amount of material between interaction point and 1st layer
  - Use high radiation length, low Z materials
  - Good stability and alignment – continuously measured and correct for
  - 100% detection efficiency
  - Fast readout to reduce pile up in high flux environments

Impact parameter*

Effect of extra mass and distance from the interaction point



GR Width	Flux increase(%) to silicon	Improvement of the IPres. wrt 1mm(%)
5mm	-44	-38.1±0.9
0.5mm	+14.1	+5.8 ±0.7
0.1mm	+27.7	+10.0 ± 0.7

*Guard Ring Width Impact on d0 Performances and Structure Simulations.

A Gouldwell, C Parkes, M Rahman, R Bates, M Wemyss, G Murphy, P Turner and S Biagi. LHCb Note, LHCb-2003-034

Why Silicon

- Semiconductor with moderate bandgap (1.12eV)
- Thermal energy = 1/40eV
  - Little cooling required
- Energy to create e/h pair (signal quanta)= 3.6eV
  c.f Argon gas = 15eV
  - High carrier yield

  $\Rightarrow$ better stats and lower Poisson stats noise
  - Better energy resolution and high signal

  $\Rightarrow$ no gain stage required

Why silicon

- High density and high atomic number
  - Higher specific energy loss
  - $\Rightarrow$ Thinner detectors
  - $\Rightarrow$ Reduced range of secondary particles
    - Better spatial resolution
- High carrier mobility $\Rightarrow$ Fast!
  - Less than 30ns to collect entire signal
- Industrial fabrication techniques
- Advanced simulation packages
  - Processing developments
  - Optimisation of geometry
  - Limiting high voltage breakdown
  - Understanding radiation damage

Disadvantages

- Cost $\propto$ Area covered
  - Detector material could be cheap – standard Si
  - Most cost in readout channels
- Material budget
  - Radiation length can be significant
    - Effects calorimeters
    - Degrades tracking due to multiple scattering
- Radiation damage
  - Replace often or design very well – see lecture 4

Radiation length X_0

- High-energy electrons predominantly lose energy in matter by bremsstrahlung
- High-energy photons by e^+e^- pair production
- The characteristic amount of matter traversed for these related interactions is called the radiation length X_0, usually measured in g cm^{-2}.
- It is both:
  - the mean distance over which a high-energy electron loses all but 1/*e* of its energy by bremsstrahlung
  - the mean free path for pair production by a high-energy photon

$$\frac{1}{X_0} = \frac{4\alpha N_A Z(Z+1) r_e^2 \log\left(183 Z^{-1/3}\right)}{A}$$