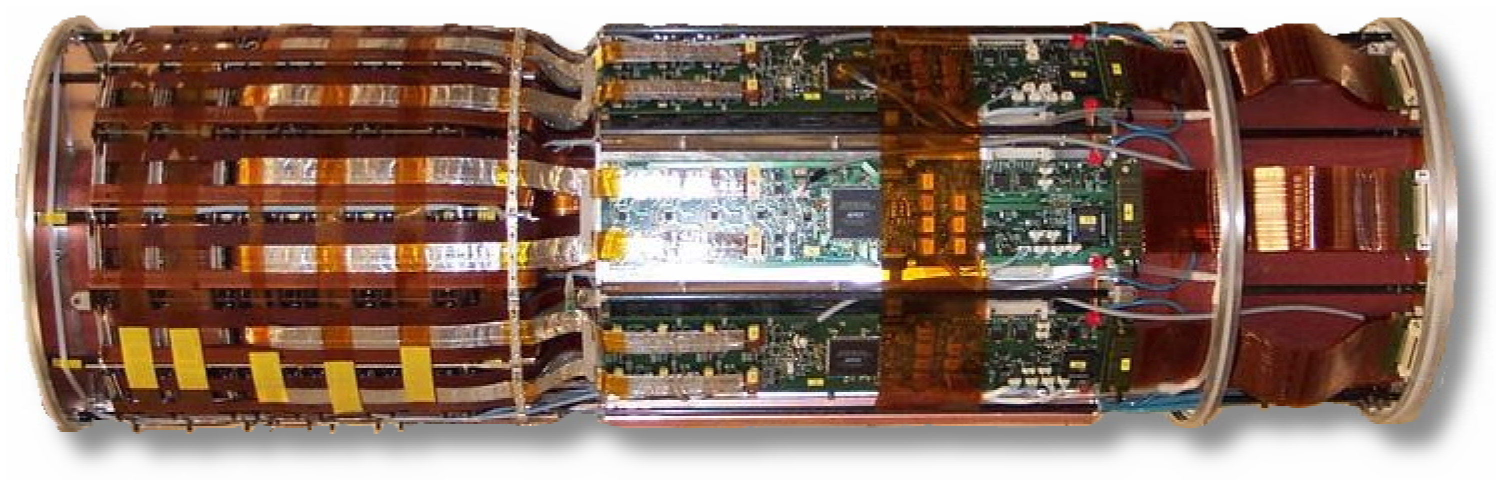
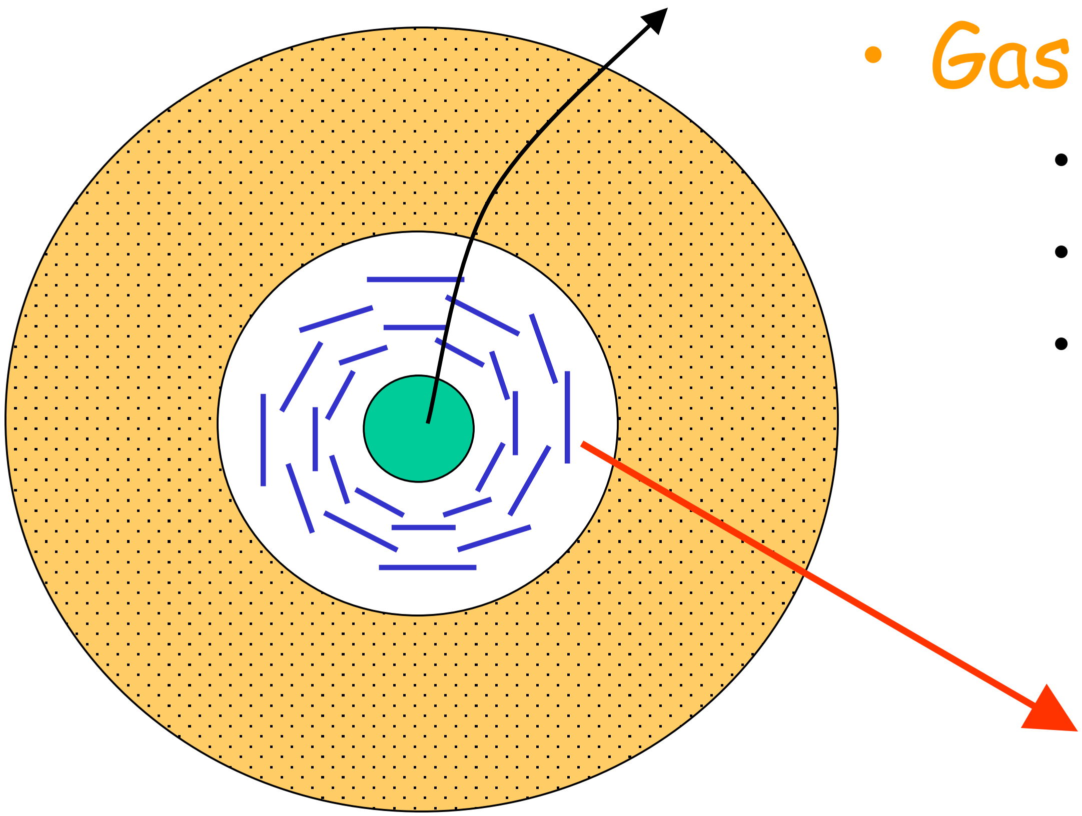
Last Lecture: Gaseous Tracking Detectors

Today: 1) `Solid State' tracking detectors
2) Track reconstruction

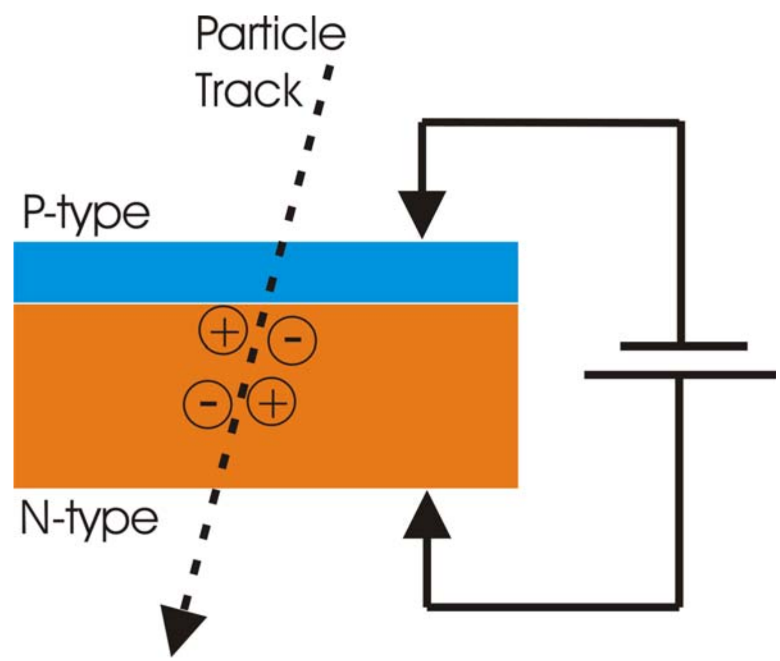


(H1 Backward Silicon Tracker)

Semiconductor Detector Context



- Gas filled detector
  - Momentum measurement
  - Many points
  - accuracy O(0.1mm



- Semiconductor detector
  - Vertex determination
  - Few points
  - accuracy O(0.001-0.01 mm)

Very Precise Tracking with Semiconductors

- 1) More precise track momentum reconstruction
- 2) Secondary vertex identification and measurement ….
  - Strong decay lifetime ~10^{-23} s, weak decay ~10^{-12} s
  - If particle moves relativistically, can travel far enough for weak decay vertex to be reconstructed ….. just!
  - … use to identify heavy flavour hadrons decaying weakly and to measure their lifetimes ….

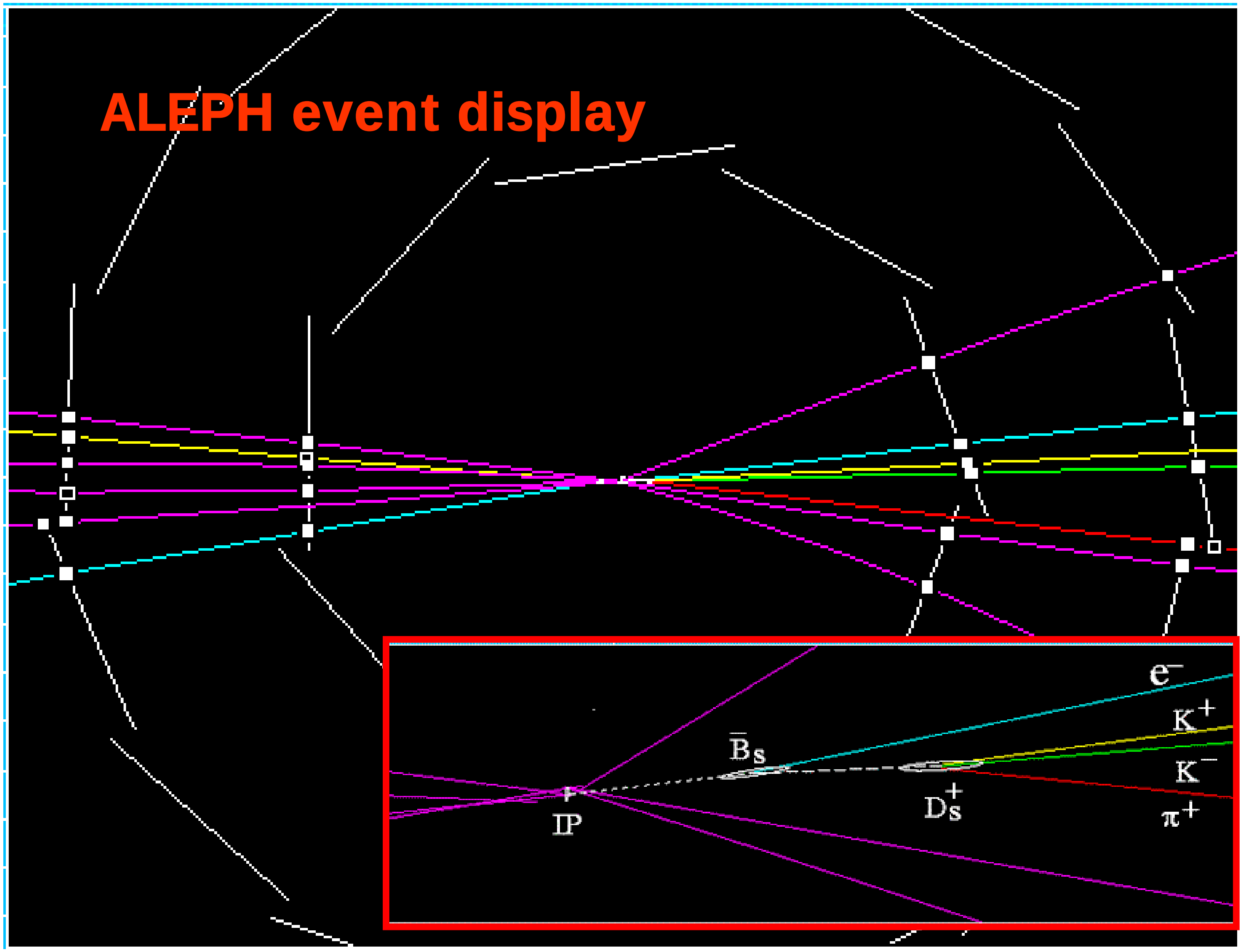
Decay	$c\tau$ (μm)
D^0	123
$D^{+/-}$	312
B^0	461
$B^{+/-}$	501

- c.f. Beam profile ~ 100 μm x 25 μm

- Need sub-100μm resolution

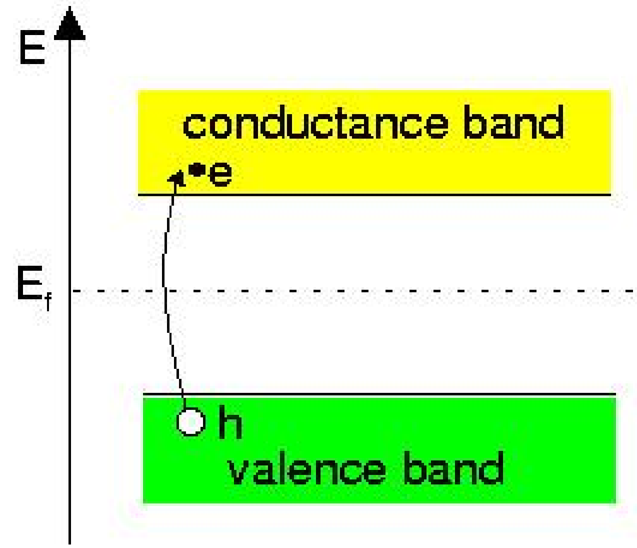
- Not possible with gaseous track detectors

A Secondary Vertex Example

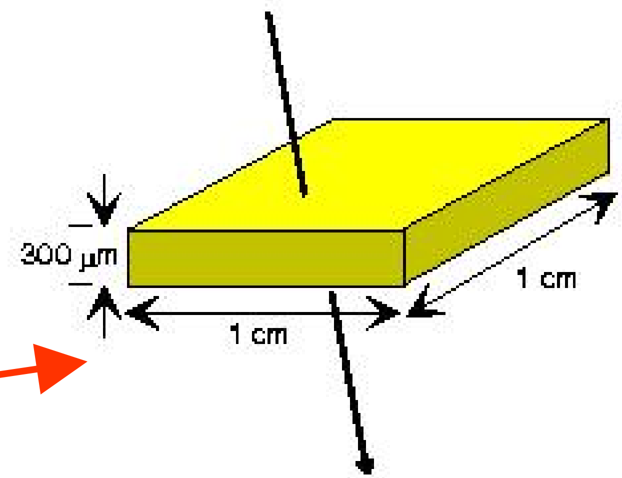


A (very little) bit of Solid State Physics

- Semiconductors are solids with small band gaps, which conduct electrically if electron-hole pairs are produced in their lattice structure.
- This could happen due to:
    - Exciting electrons with thermal energy (Boltzmann dist^n)
    - A passing ionising particle

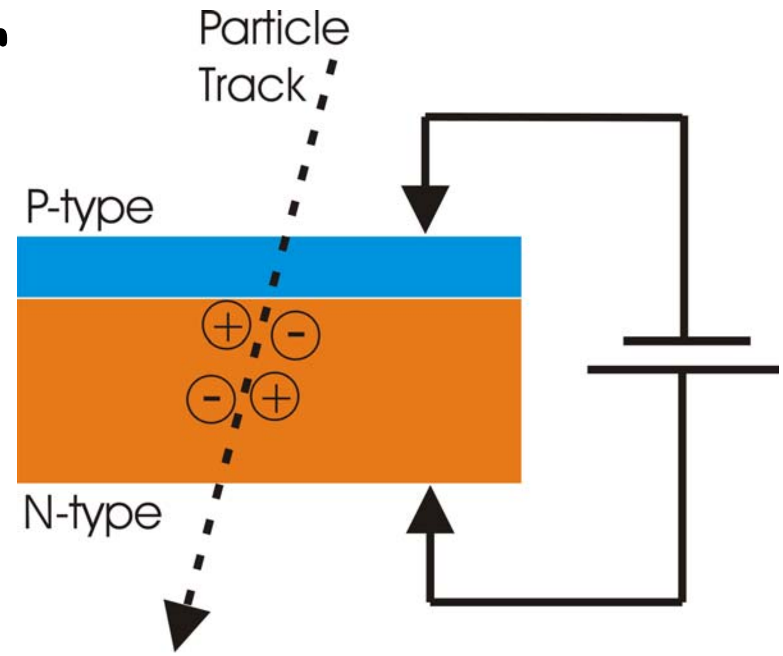


- A solid state device detects the e-h pairs ("free carriers") produced by passing charged particles …



Thermally excited e-h pairs are a nuisance … this much silicon contains ~4.5 x 10^8 free carriers at room temperature. A minumum ionising particle produces ~3.2x10^4

A Semiconductor Detector



- The solution is to make a `pn junction' (like a diode), but with a `strong reverse bias', increasing energy required to produce e-h pairs thermally.

Full detector is then `depletion region' … electron-hole pairs **ONLY** appear when a charged particle passes by.

- For our purposes, just another ionisation detector, but using thin layers of (solid) semiconductor instead of gas … … electron-hole pairs drift to electrodes in E field to give signal … precise due to small size

	Ideal	Gas	Solid
Density	Low	Low	High
Atomic Number	Low	Low	Moderate
Energy to Ionise	Low	Moderate	Low
Signal Collection	Fast	Moderate	Fast

Semiconducting Materials

Various types available…

- Germanium, GaAs used in the past
- Diamond interesting but expensive!
- Silicon more or less universally used for modern HEP applications …

… Good availability (though ATLAS and CMS are demanding!)

… Small band gap (3.6eV makes an e-h pair, c.f. 30 eV in a gas detector)

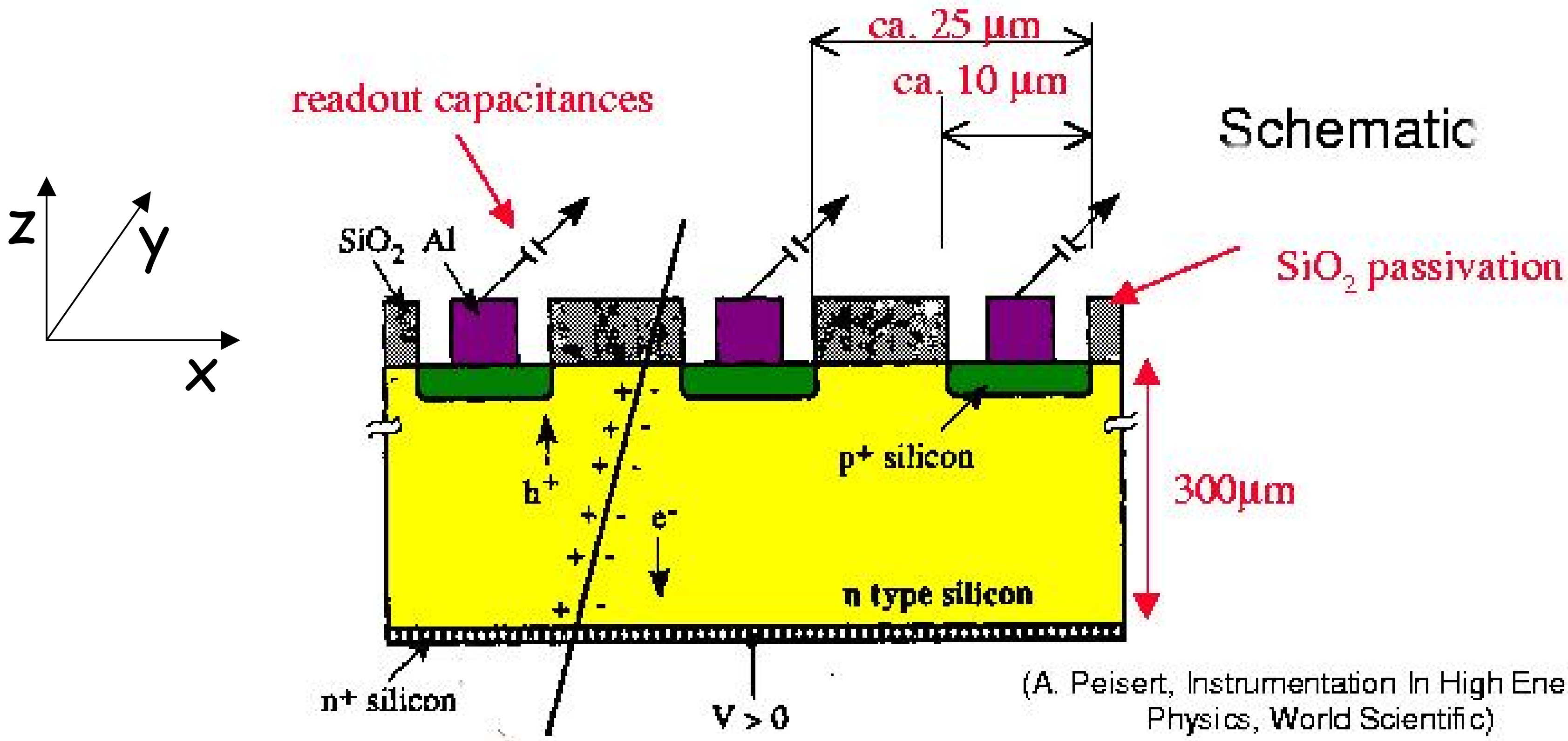
… Large scale designs with strange shapes are possible.

IIIA	IVA	VA
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674
13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761
31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160
49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760
81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038

Main difficulty … radiation hardness ☹

Silicon Microstrip Detector

x direction info by segmenting p doped layer, pitch ~ 25μm.
… resolution can be very good: σ ~ pitch / sqrt(12)



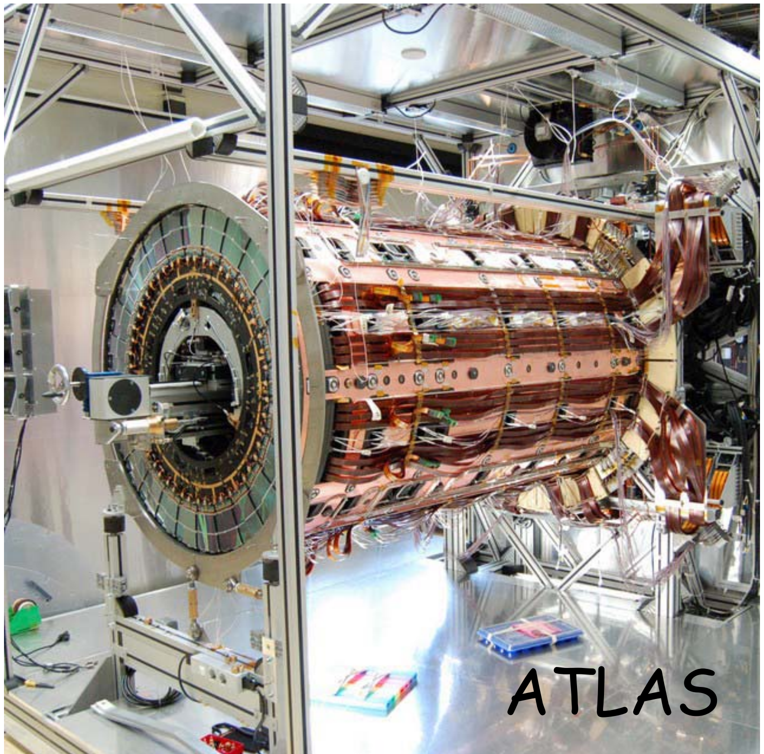
(A. Peisert, Instrumentation In High Energy Physics, World Scientific)

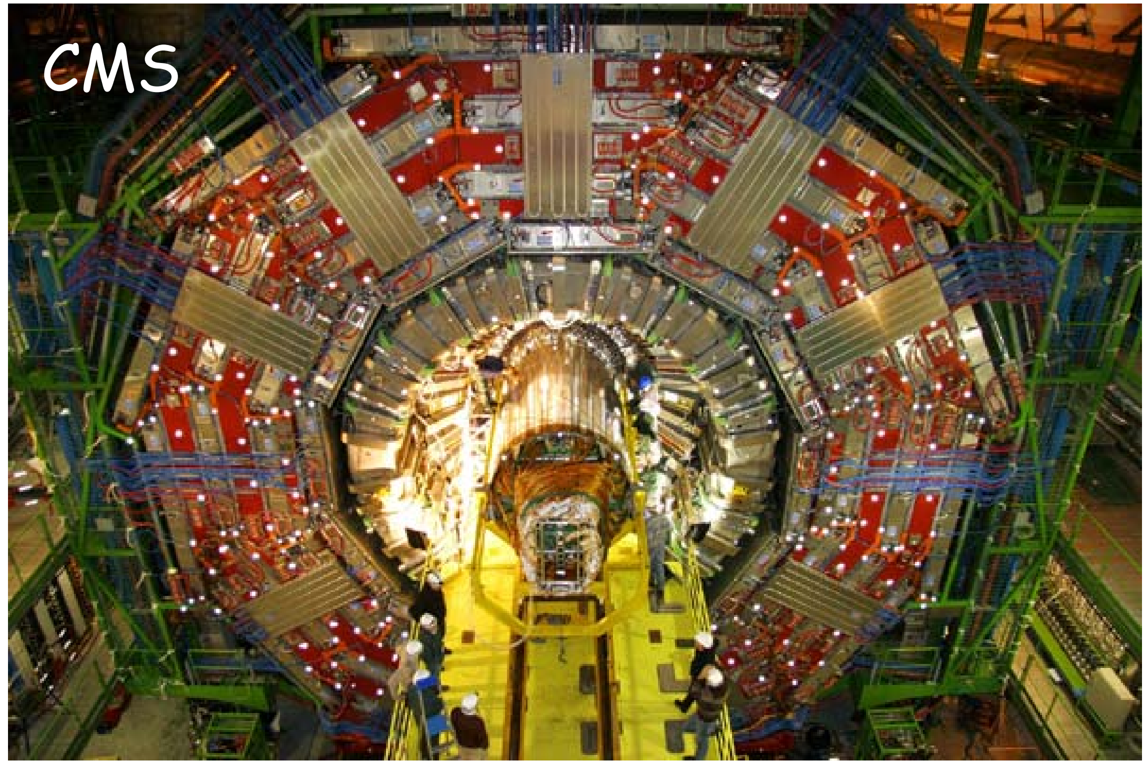
- Strips are several centimetres long in y direction … perpendicular double layers for (x,y) dimensional info

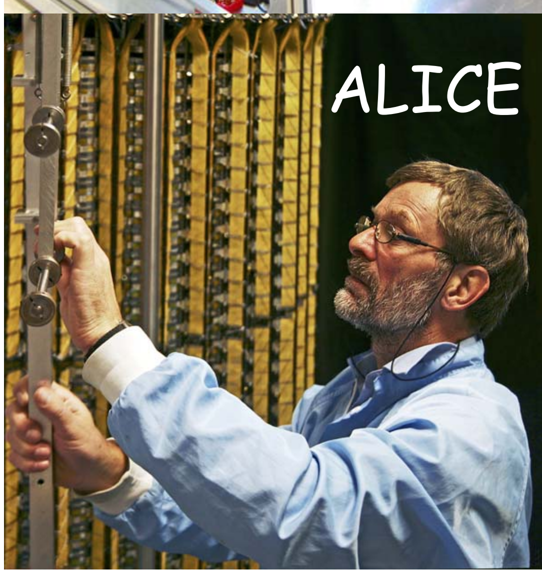
H1 Central Silicon Tracker (2 sided strips)

This little beast has 100,000 readout channels …
… and it is far from state-of-the-art …

Silicon Detectors at the LHC – a new scale!

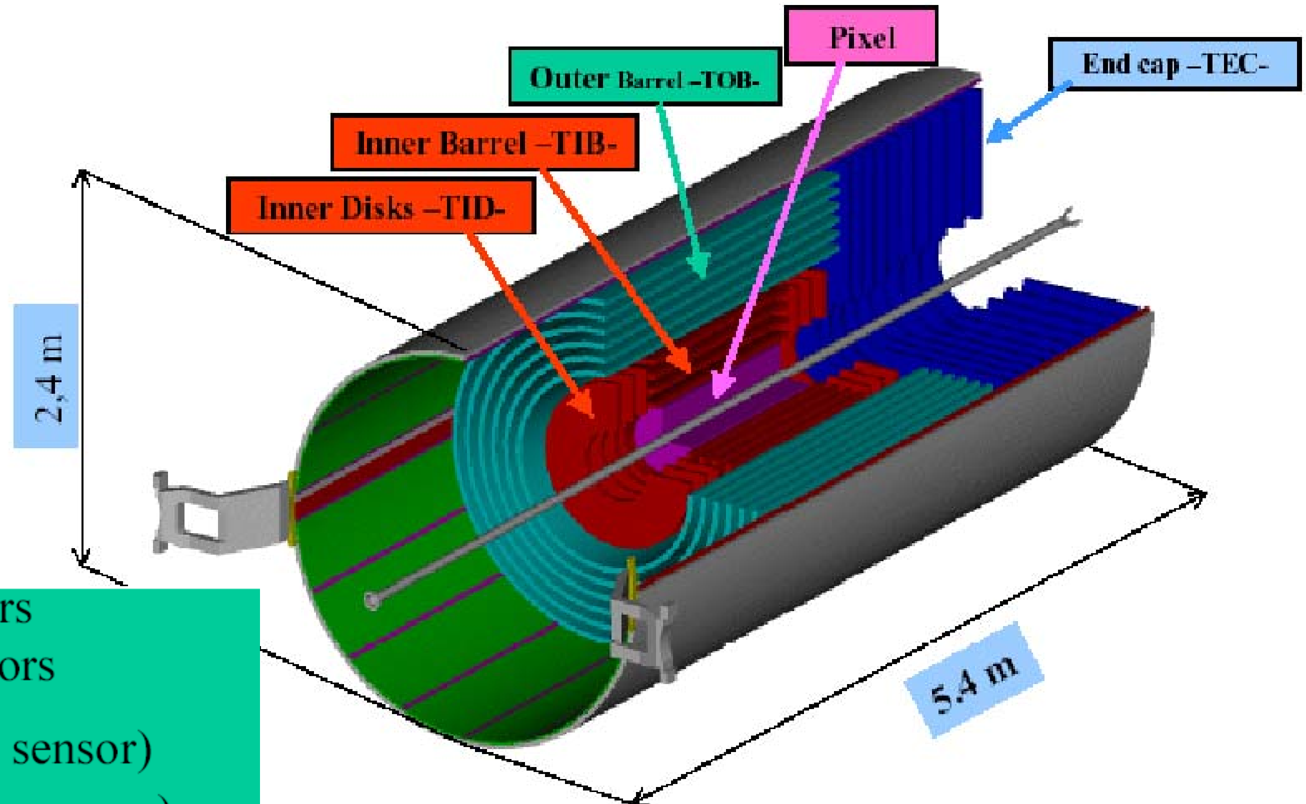






… e.g. CMS built entire tracking region from silicon (does this explain why it weighs so much?!?!)

CMS Silicon Strip Detector



6,136 thin sensors
18,192 thick sensors

6,136 thin detectors (1 sensor)
9,096 thick detectors (2 sensors)

3,122 + 1,512 thin modules (ss + ds)
5,496 + 1,800 thick modules (ss + ds)

9,648,128 strips ≡ electronics channel

75,376 APV chips subμ

25,000,000 bonds

440 m^2 of silicon wafers
210 m^2 of silicon sensors

Immense project – huge volume of silicon

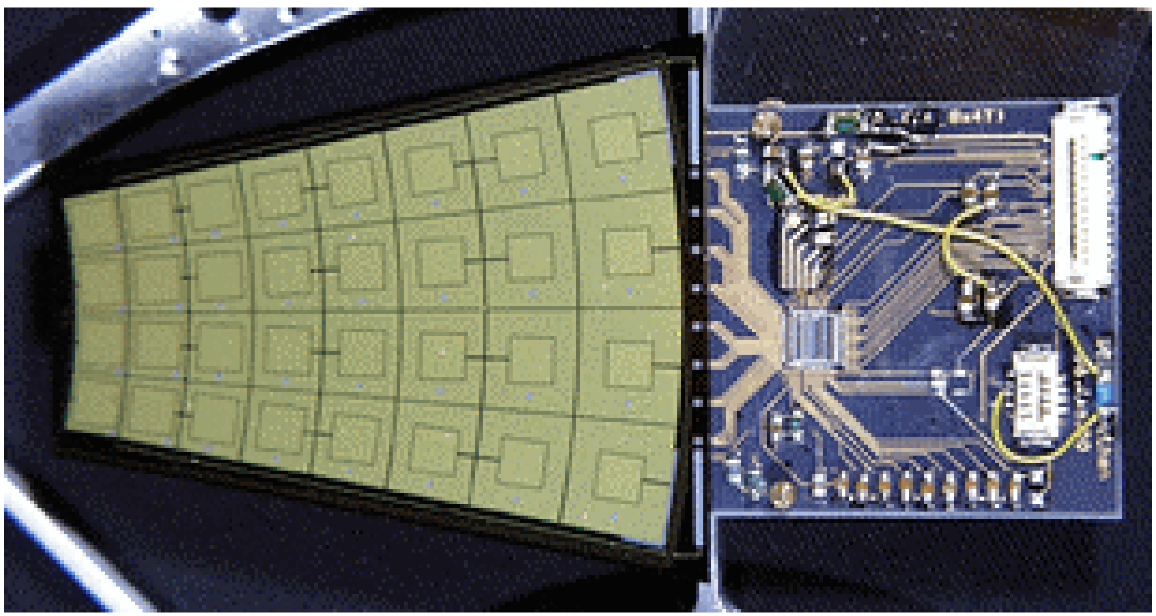
10 million readout channels!

How to Get 2(3) Dimensional Silicon Tracking

Double-sided Strip Detector

Also dope and segment the `bottom' of the N-type material with orientation perpendicular to the top!

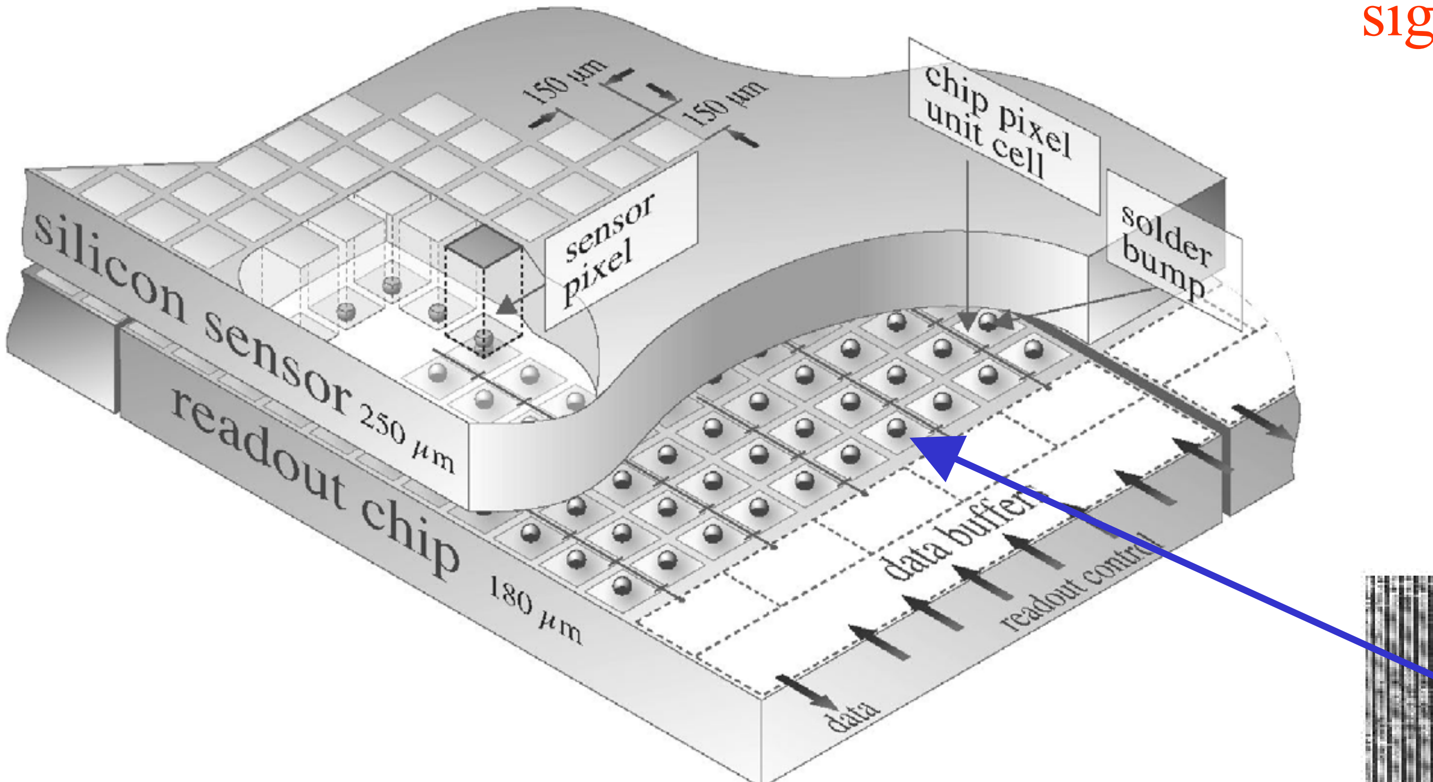
Pad Dectors

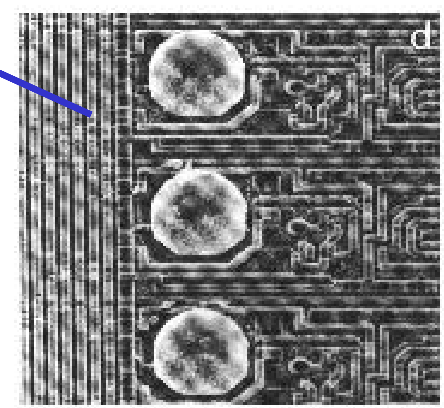


- Build detector with small square pads instead of strips
- Pads are typically 1mm x 1mm, so similar resolution to strips
- Readout electronics attached directly to detector

Pixel Detectors

Much smaller version of pad detector (e.g. 150 μm x 150 μm)
Requires sophisticated readout! – Electronics with same geometry connected to each pixel with bump bonding techniques to get the signal out!

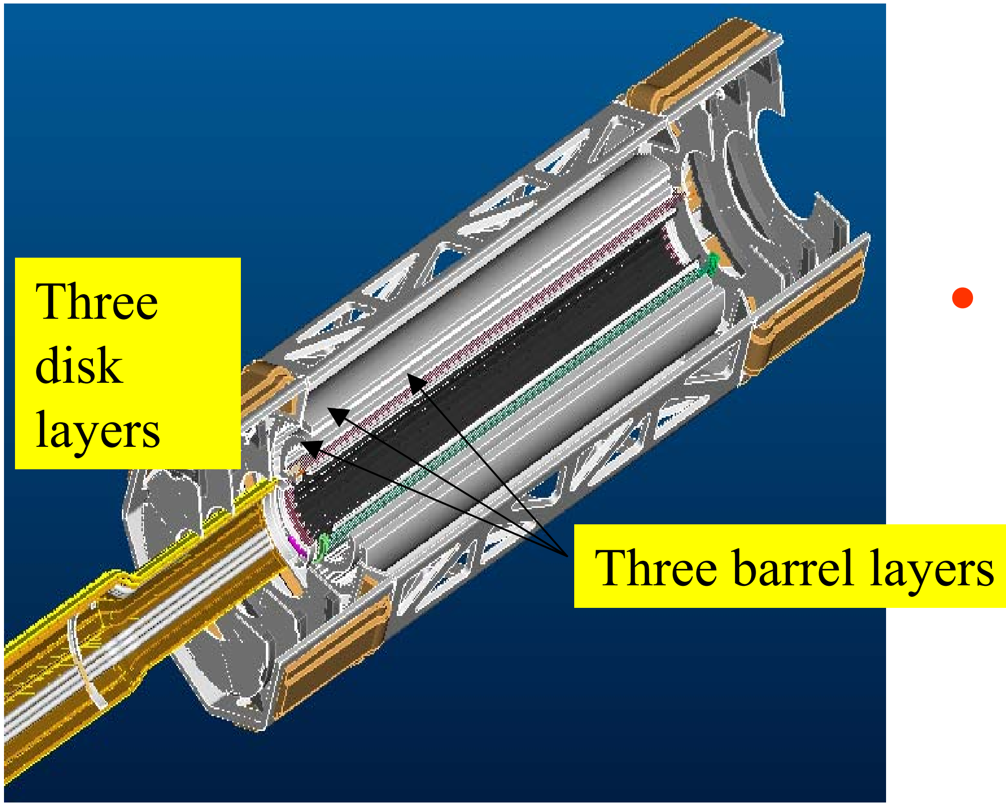




Used in both CMS and ATLAS innermost regions

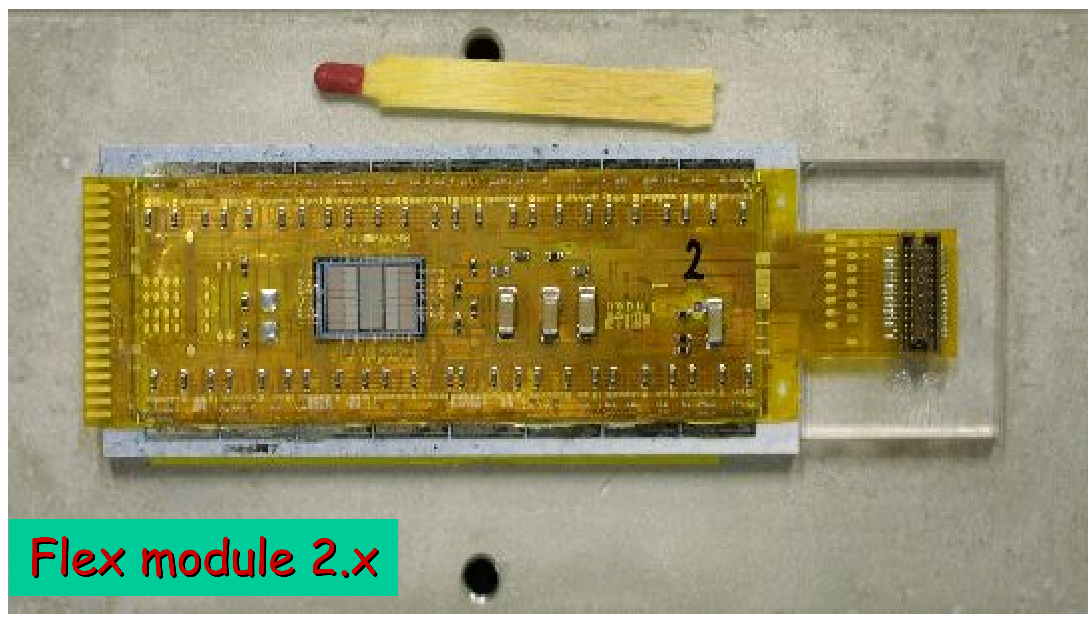
ATLAS Pixel Detector

- ~2.0 m^2 of sensitive area with 0.8×10^8 channels



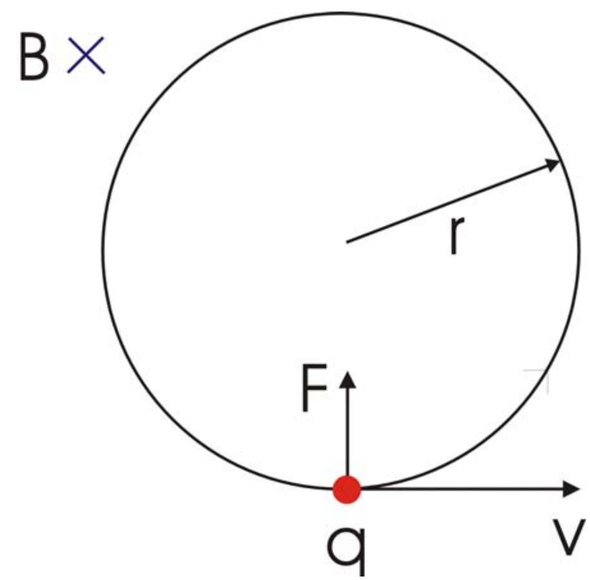
Silicon pixels

(50 μm × 300 μm)



Particle Momentum Reconstruction

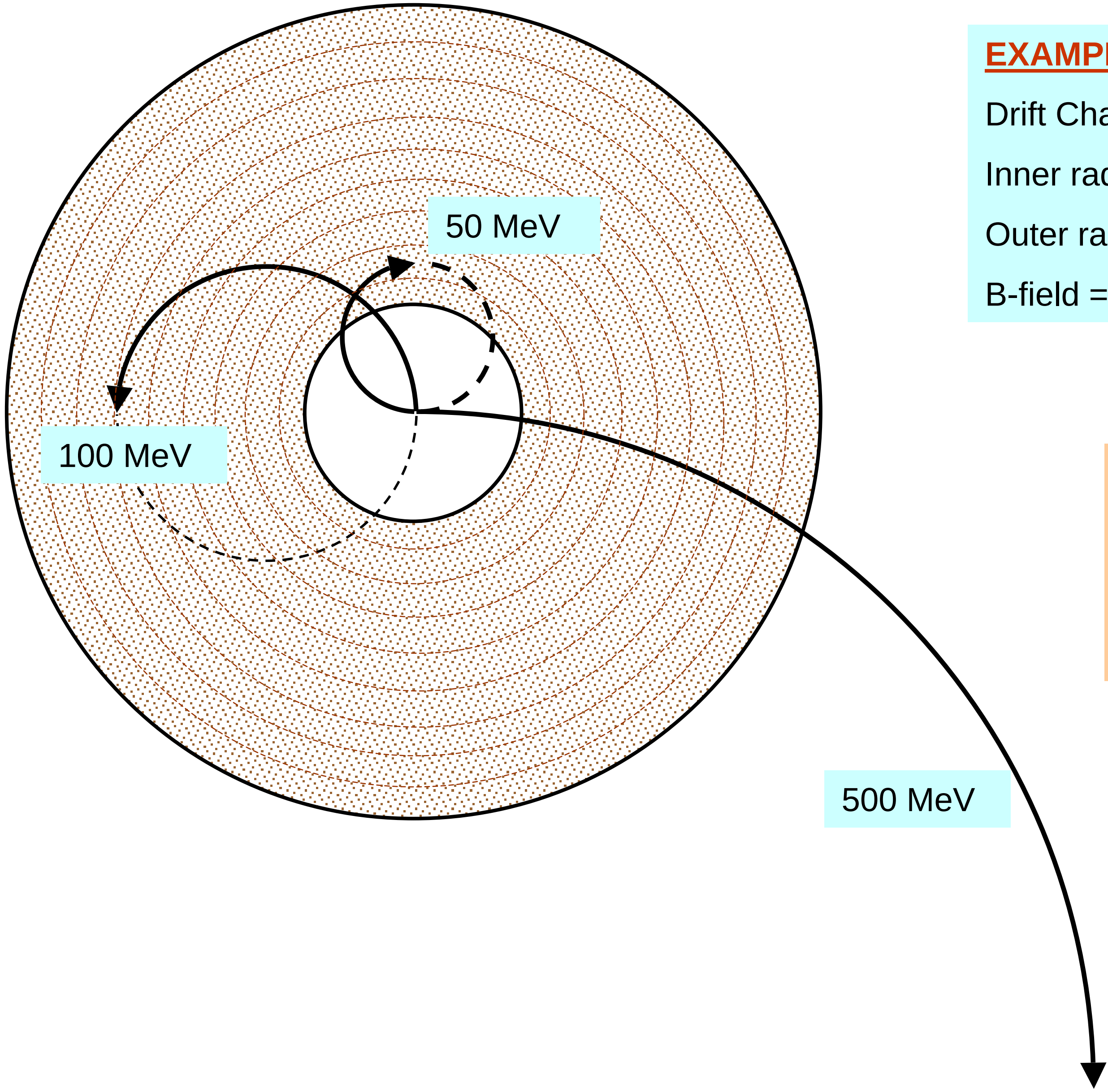
- Consider motion in rϕ plane (B field uniform and parallel to beam)
- Moving charged particle feels force
F = q **B** x **v**
- Force always perpendicular to motion, so changes direction, but not kinetic energy
- If field is uniform, motion in rϕ plane must be a **circle**. Radius is $\mathbf{r = p_t/qB}$



With B in Tesla, pt in GeV and r in metres, $\mathbf{r=p_t/0.3B}$

- Motion in z direction is constant (no effect from parallel B field)
- So 3 dimensional trajectory is a **helix**.

Example 1



EXAMPLE: ZEUS

Drift Chamber

Inner radius 16 cm

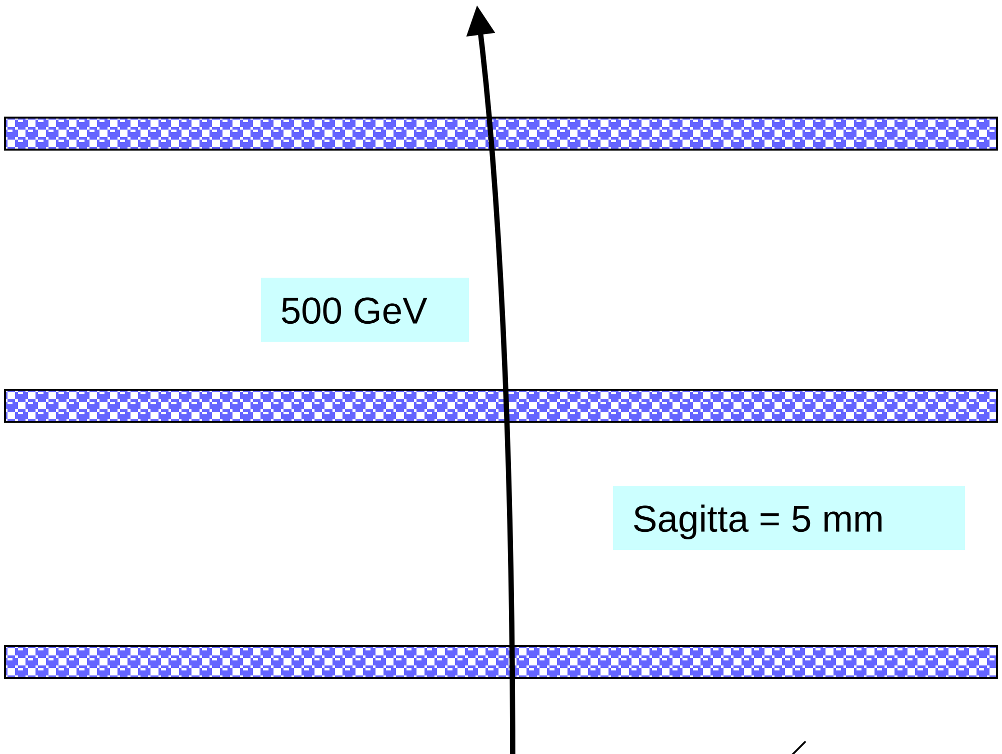
Outer radius 85 cm

B-field = 1.5 Tesla

$$\text{radius} = \frac{1}{\rho}$$

$$\rho = \frac{0.3\,B}{p \cdot \sin\theta}$$

Example 2



EXAMPLE: ATLAS

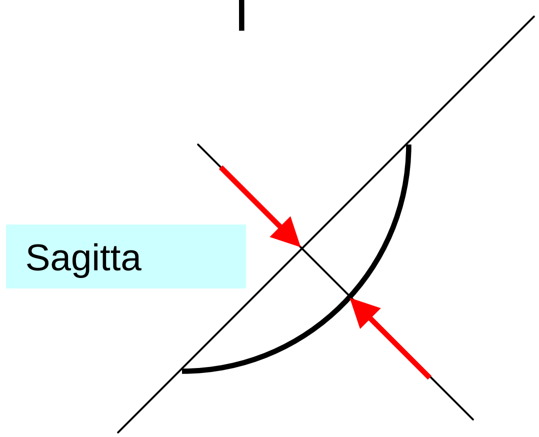
Drift tubes

Inner radius 5 m

Middle radius 10 m

Outer radius 15 m

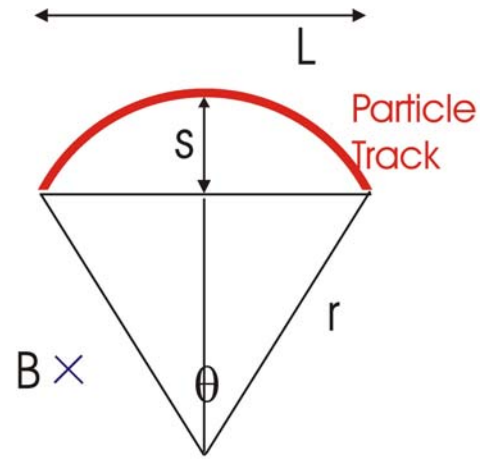
B-field = 0.6 Tesla



$$\text{radius} = \frac{1}{\rho}$$

$$\text{Sagitta} = \frac{L^2}{8\rho}$$

How it works in Practice: the Sagitta



- Drift chamber gives a track segment about chord of the circle described by the particle.
- In practice, measure the **sagitta s** in order to reconstruct p_t.

$s = L^2 / 8r = qBL^2 / 8p_t$

… hence obtain p_t from s …

$\sigma(p_t)/p_t = \sigma(s)/s = [8 / (q\ B\ L^2)]\ .\ p_t\ .\ \sigma(s)$

- resolution degrades α p_t
- σ(s) depends on number of wires (points in track segment)

For an accurate pt measurement, want low p_t

high B field

long chord, L

lots of hits on segment

lots of separate segments

Momentum Uncertainty for Trackers

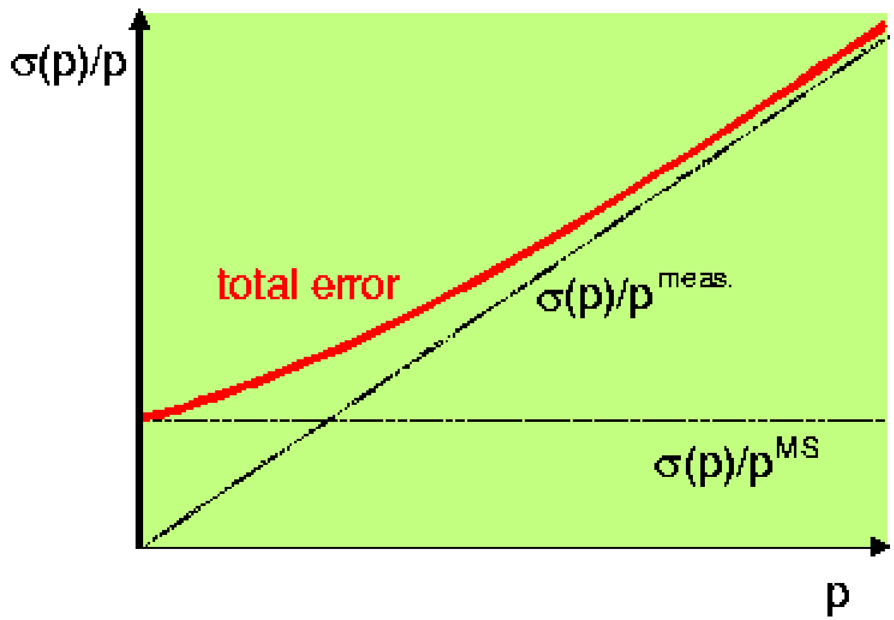
- For high momenta, uncertainty is dominated by sagitta measurement

- As momentum becomes very small, multiple elastic Coulomb scattering takes over -> lots of small deflections in angle, no energy loss

-Error on the momentum measurement is independent of p

$$\left.\frac{\sigma(p)}{p_T}\right|^{MS} = 0.045\frac{1}{B\sqrt{LX_0}}$$

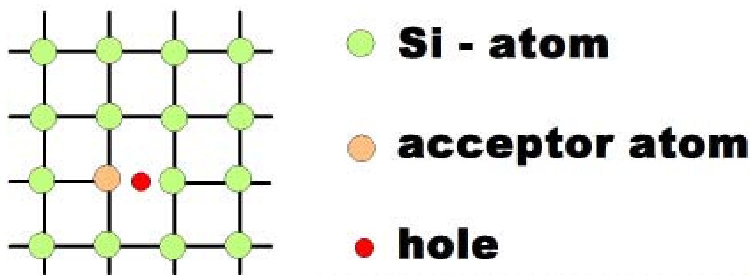
X_0 is the radiation length of material



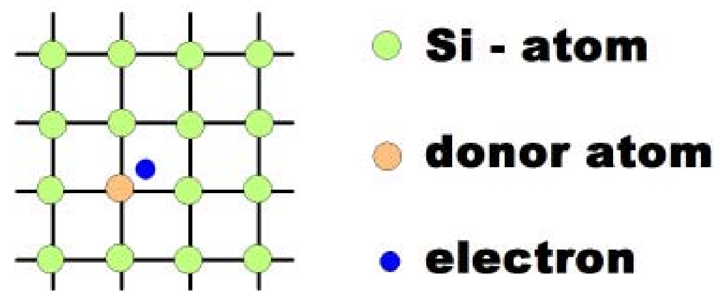
If you want precision, minimise dead material e.g. in beampipe!

BG info: Doped Semiconductors and Depletion

P-type



N-type



Holes are majority carriers

Electrons are majority carriers

- Placing p and n types together leads to diffusion …space charge builds up, →depletion region stopping further transfer. (a DIODE).
- Apply forward bias (voltage) to make it conduct
- Apply backward bias to increase depletion region & remove all free thermal carriers… solid state detector!