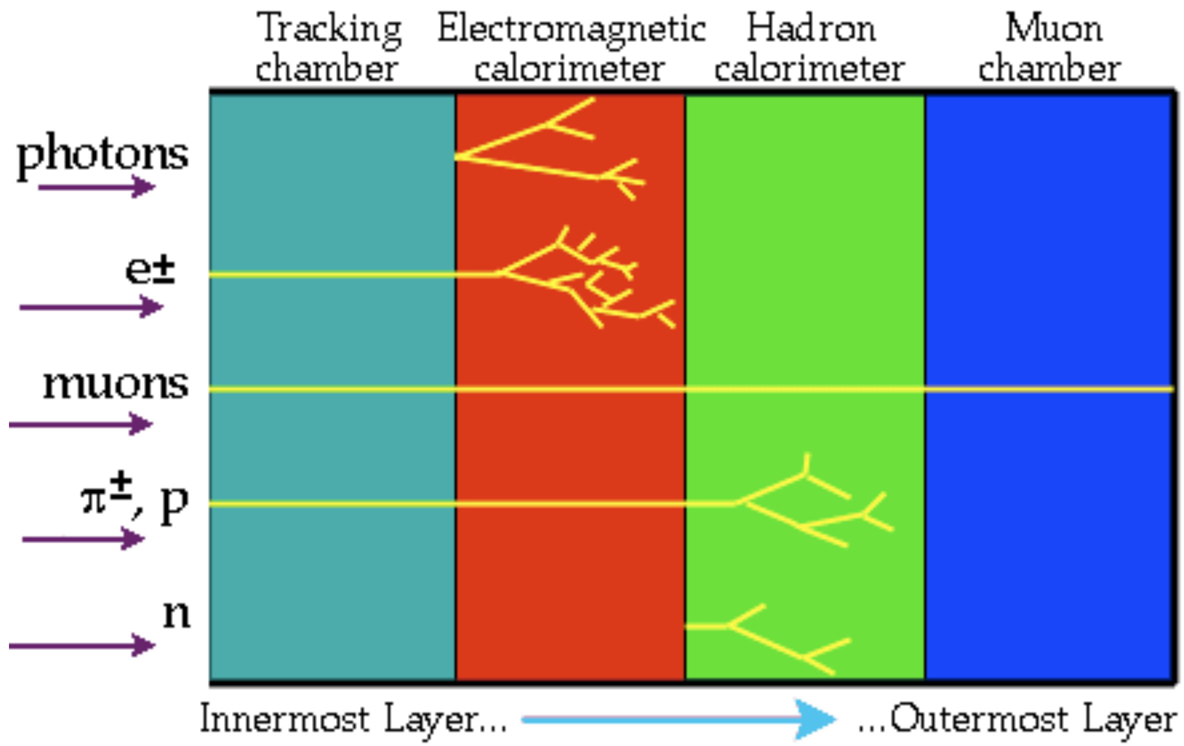
Lecture 24

Components of a generic collider detector

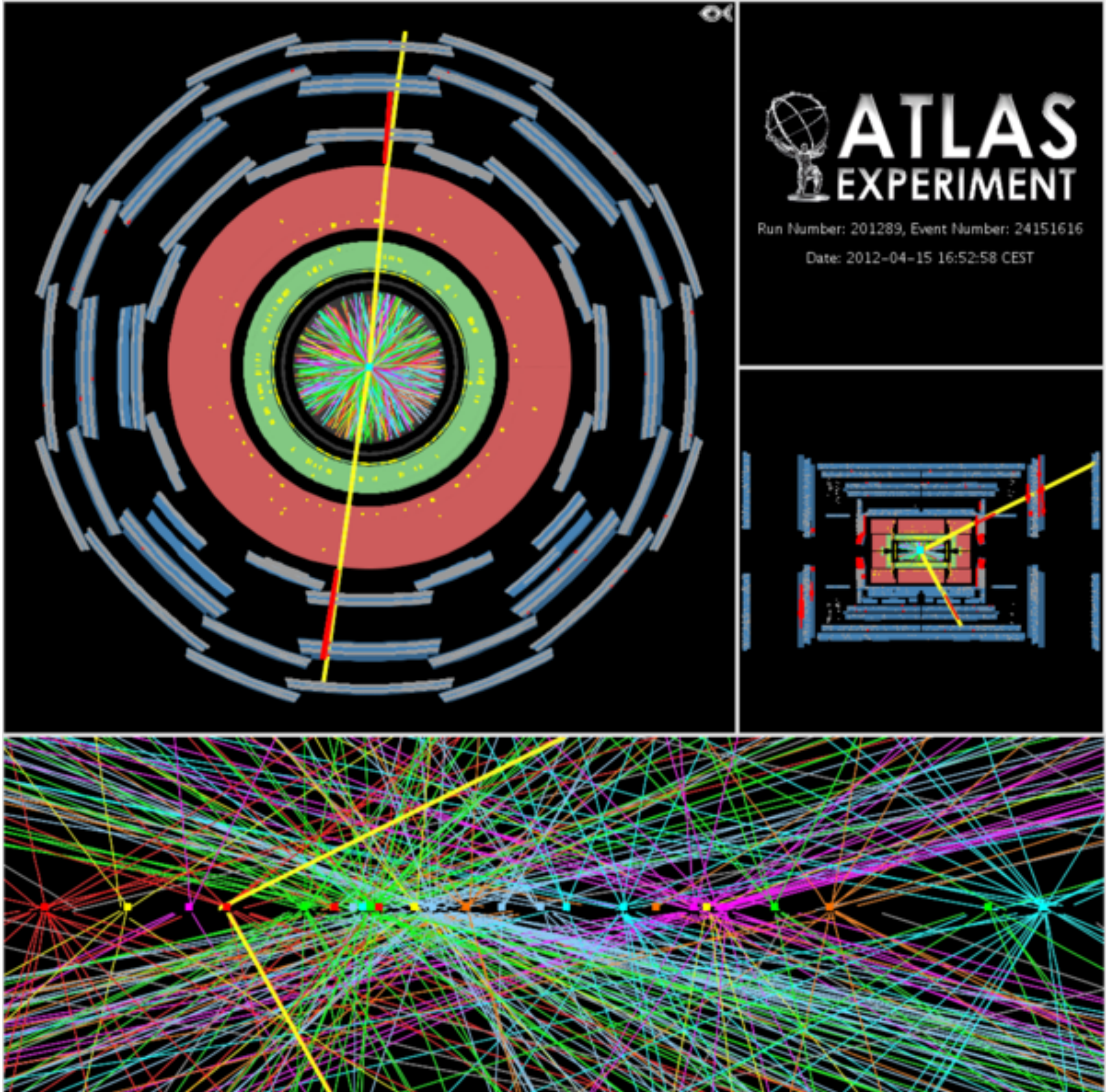


electrons - ionization + bremsstrahlung
photons - pair production in high Z material
charged hadrons - ionization + shower of secondary interactions
neutral hadrons - no ionization but shower of secondary interactions
muons - ionization but no secondary interactions

Tracker requirements

- Minimize mass inside tracking volume
  minimal distortion of calorimetric measurement
- Minimize mass between interaction point and detectors
  minimal distortion of track trajectory due to scattering
- Minimize the distance between interaction point and the detectors
  allow for measurements of secondary vertexes due
  to decay of particles with short lifetime (B mesons, τ leptons)
- Good spatial resolution to resolve close tracks
- Must work in magnetic field
- Fast readout
- High efficiency
- Affordable cost

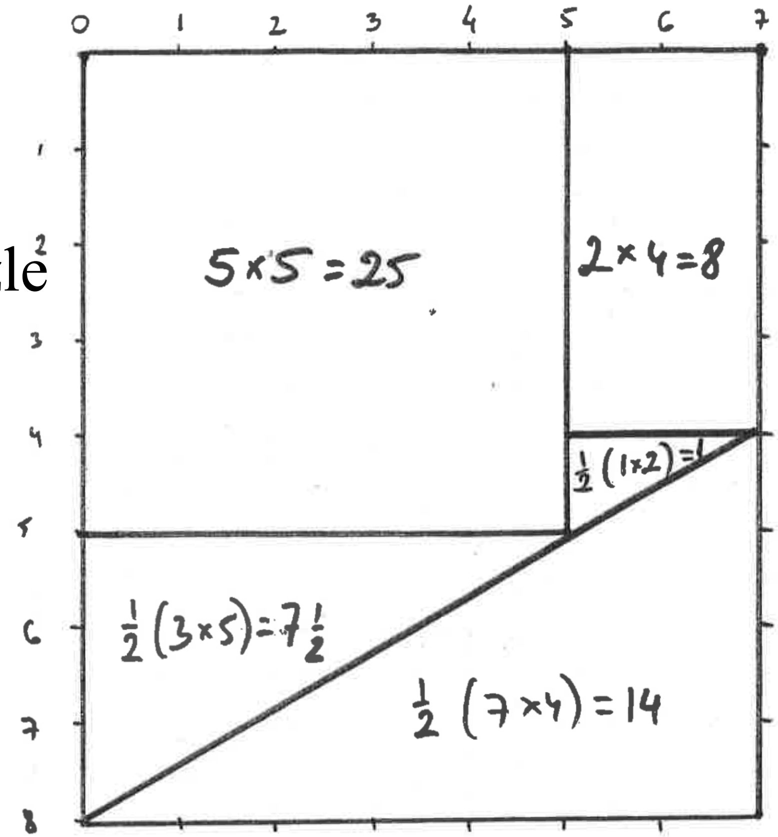
……..



bunch length = 5 cm →

The need for precision

5th grade puzzle



$25+8+1+7\frac{1}{2}+14 = 55\frac{1}{2}$

$7 \times 8 = 56$

ATLAS

Tracking length L = 1.15 m B field = 2 T

p = 50 GeV/c ρ = 144.9 m sagitta = 0.0011m (1.1 mm)

p = 1000 GeV/c ρ = 1666.7 m sagitta = 0.0001m (0.1 mm)

Tracking Systems: ATLAS (2012)

Pixel Detector

3barrels, 3+3 disks: 80×10^6 pixels

barrel radii: 4.7, 10.5, 13.5 cm pixel

size 50×400 μm

$\sigma_{r\phi}$= 6-10 μm σ_z = 66 μm

SCT

4barrels, disks: 6.3×10^6 strips

barrel radii:30, 37, 44 ,51 cm strip

pitch 80 μm

stereo angle ~40 mr

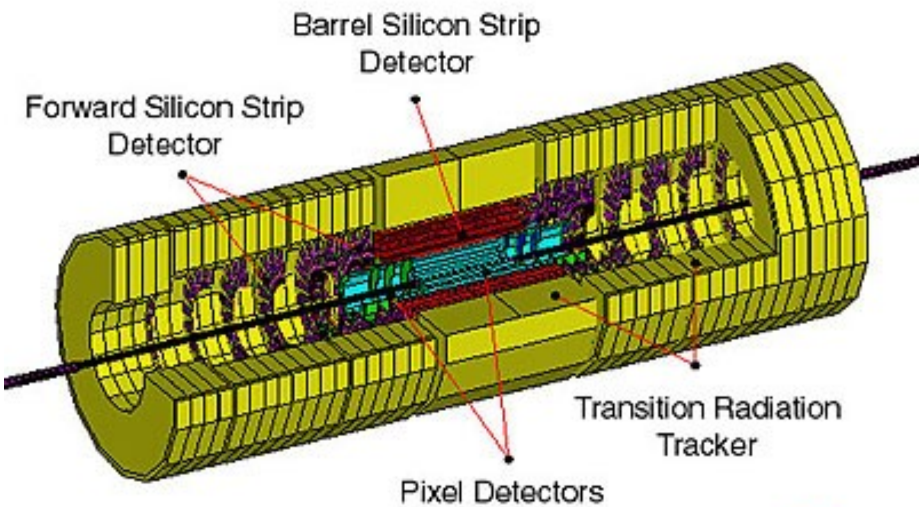
$\sigma_{r\phi}$= 16 μm σ_z = 580μm

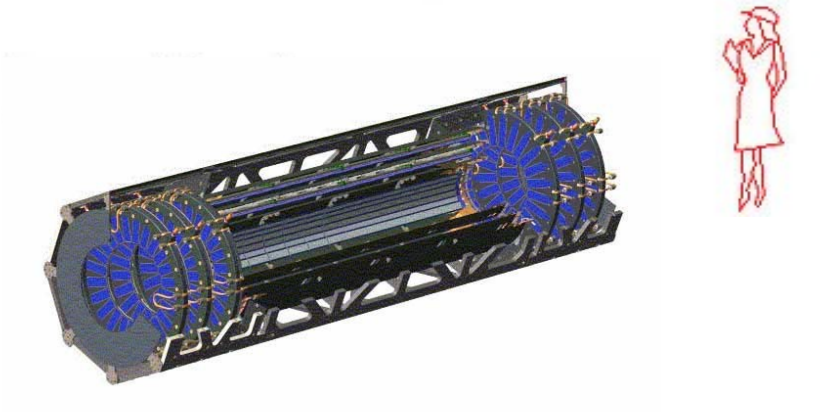
TRT

barrel: 55 cm < R < 105 cm 36 layers

of straw tubes $\sigma_{r\phi}$= 170 μm

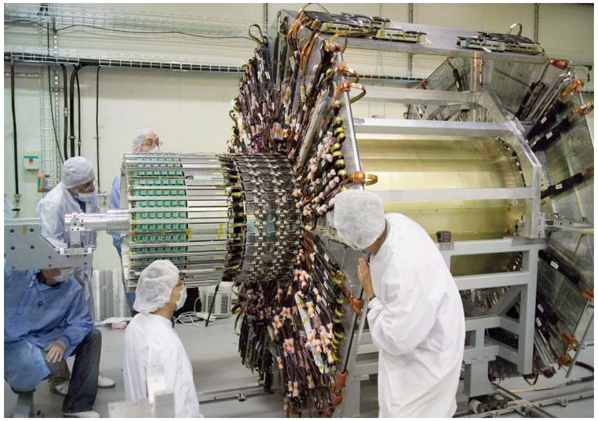
400.000 channels



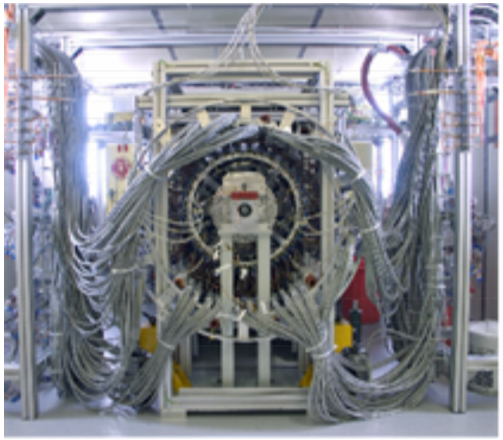


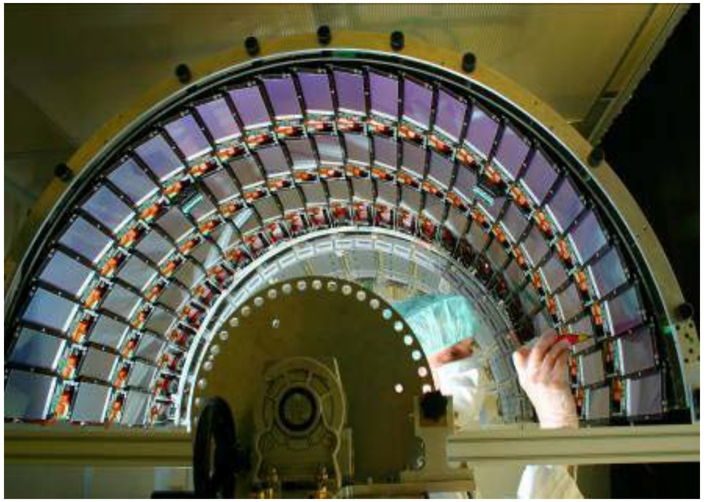
+ IBL (2016)

Tracking Systems: ATLAS & CMS



ATLAS

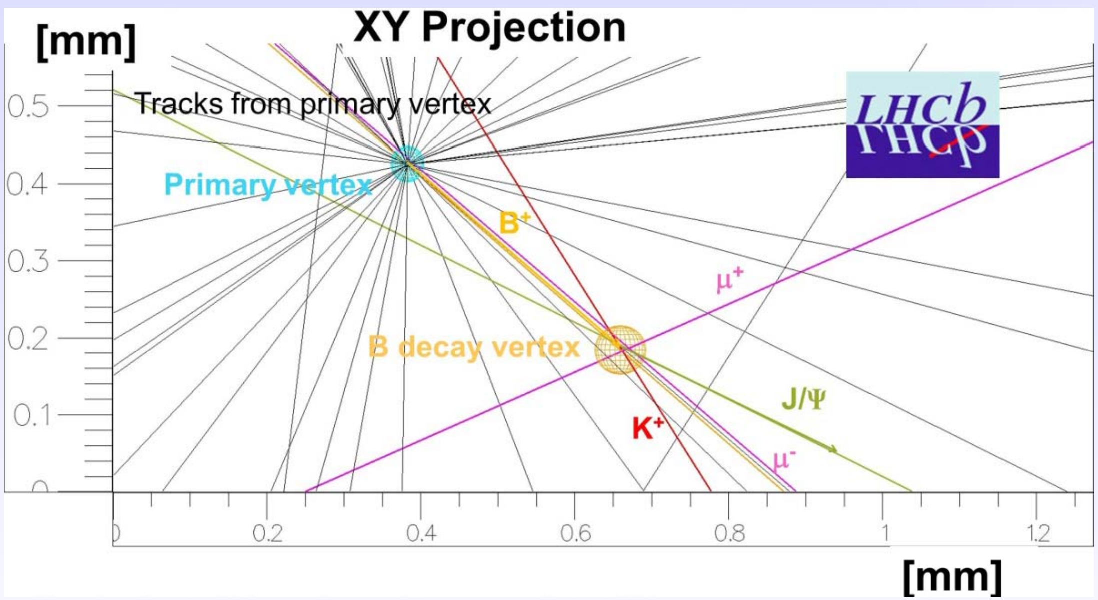


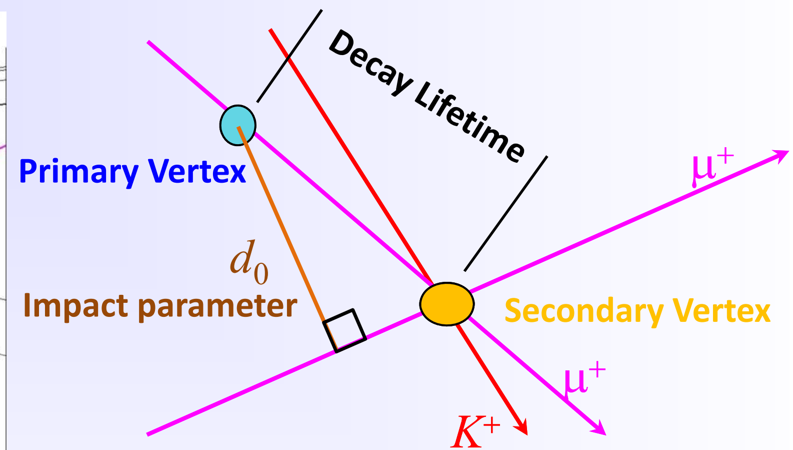


CMS

Primary and secondary vertex

- Primary and Secondary Decay Vertices
  - *Example*: B lifetime $\tau_B \sim 1.6$ ps $\Rightarrow \gamma c\ \tau_B = \gamma \cdot 500\ \mu m$ with $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$
  - Figure of merit: **Impact parameter resolution**
  - Physics example from LHCb (2010) : $B^+ \rightarrow J/\Psi\ \ K^+$

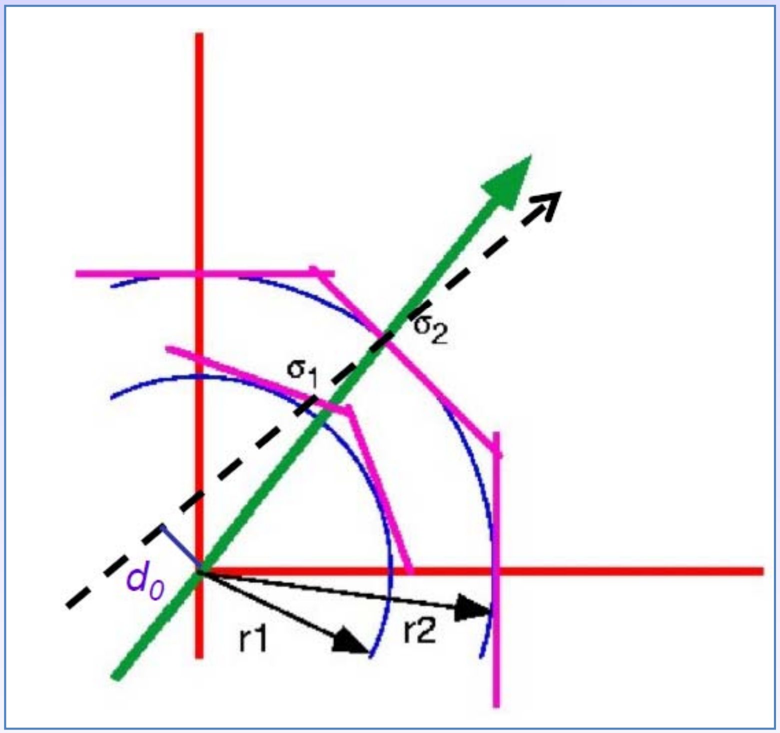




- mean path length λ of a meson with b quark or a τ lepton ~ 2 mm
- fraction visible in transverse plane ~2/3 λ
- → need sub-mm measurement precision

- Uncertainty on the transverse impact parameter, d0, depends on the detector radii and space point precisions.

- Simplified formula for just two layers:



$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{\left(r^2 - r^1\right)^2} + \sigma_{MS}^2$$

– Suggests small r_1, large r_2, small σ_1, σ_2

– But precision is degraded by multiple scattering .

Example: **LHCb (VELO)**

σ(IP)= (10 + 29/p_T[GeV/c]) μm [PoS VERTEX2010:014,2010.]

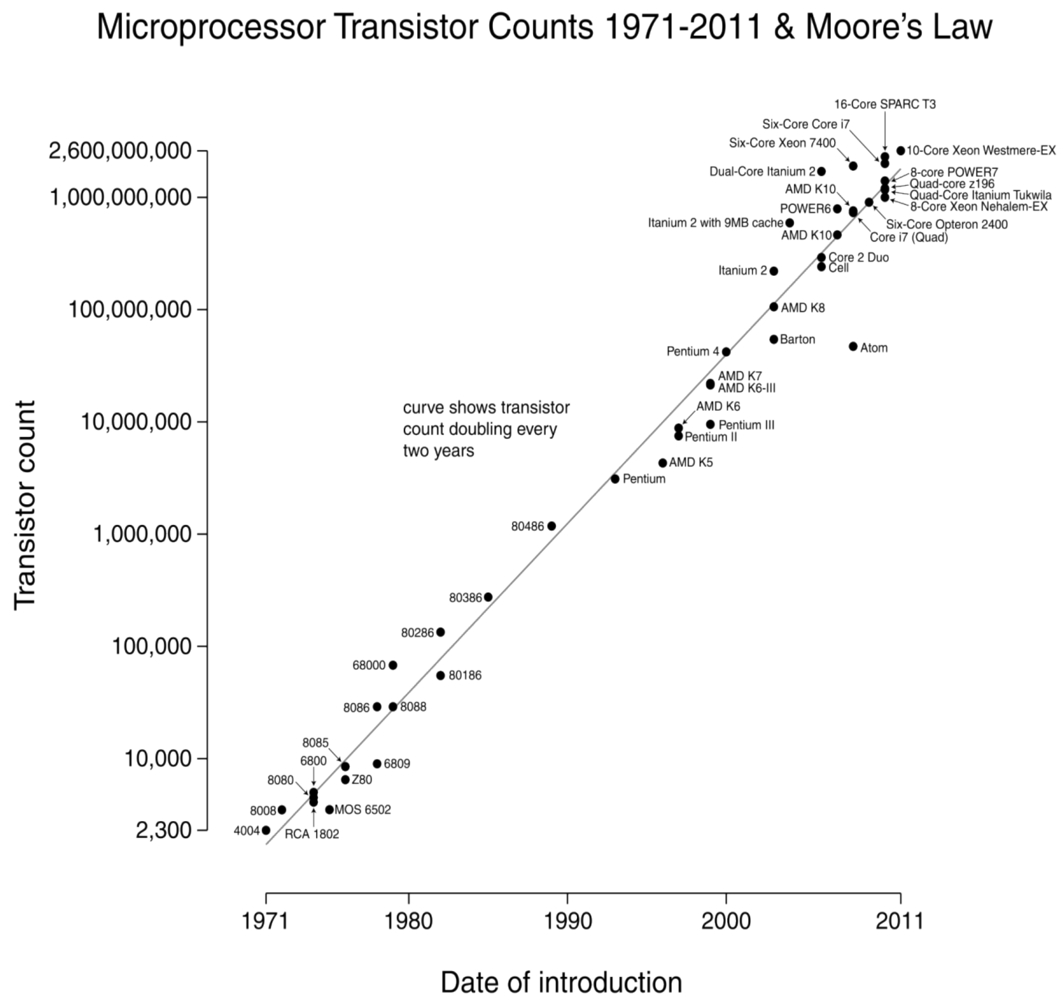
from Michael Moll

Semiconductor detectors

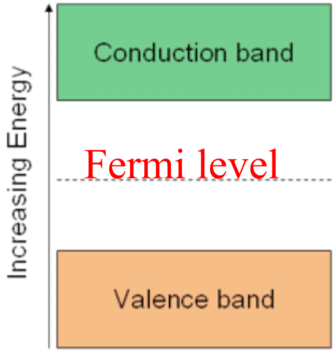
Why Si or Ge?

Detector production by microelectronic technique
- leverage progress in integrated circuits technology
- small dimensions
- silicon rigidity allows for thin support structure

\- Moore's Law transistor count doubling every two years

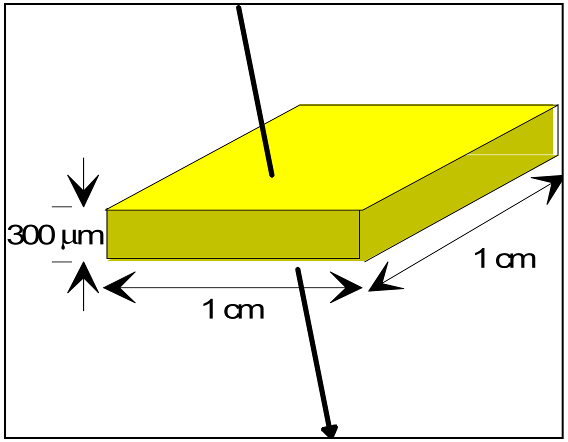


Semiconductor



Pure undoped Si – electron density 1.45×10^{10} cm^3

Fermi level – Maximum electron energy at T = 0 K



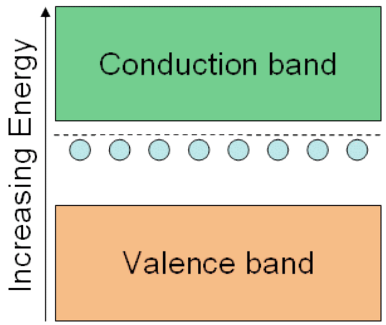
In this volume there are 4.5×10^8 free charge carriers, but only 2.3 10^4 e-h pairs produced by a M.I.P.

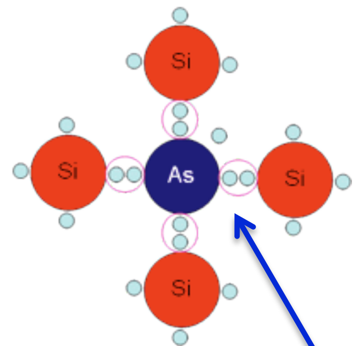
-> Reduce number of free charge carriers
i.e., deplete the detector

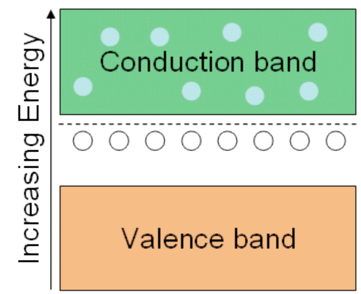
Typically make use of reverse biased p-n junctions

Doped semiconductor

DONOR (N)



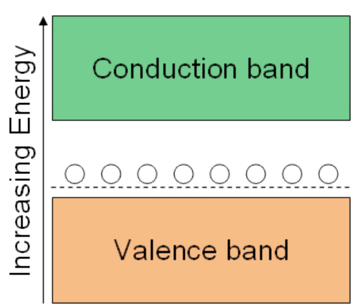


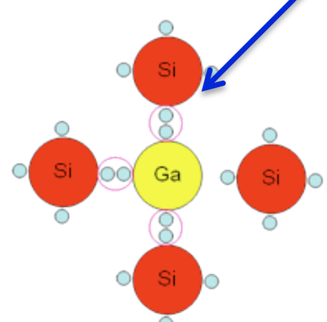


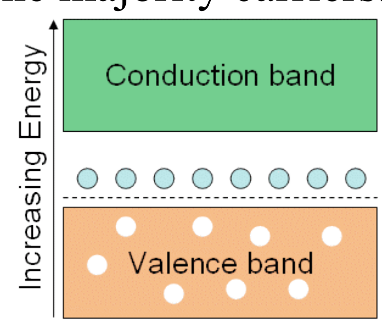
Add elements from V^{th} group, donors,
e.g. Arsenic - As.
Electrons are the majority carriers.

ACCEPTOR (P)

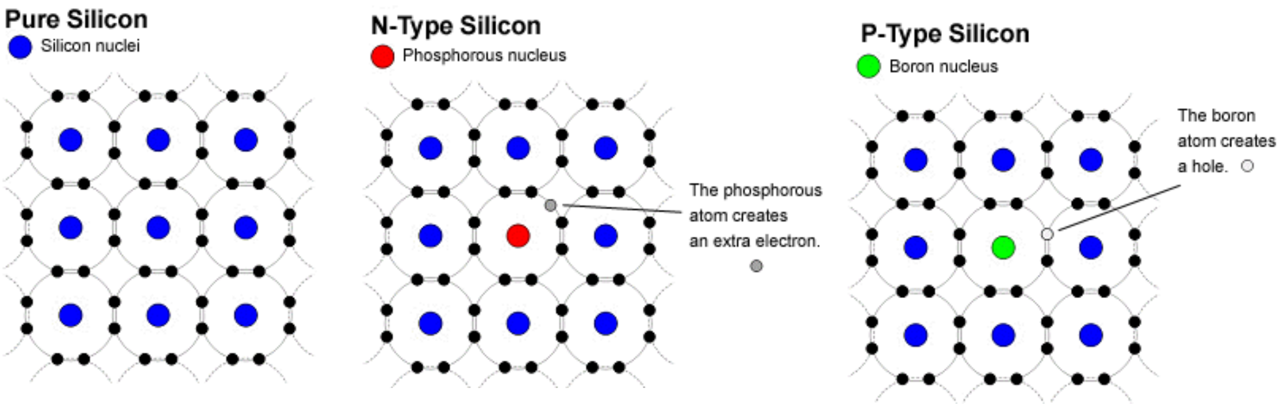
Add elements from III^{rd} group, acceptors,
e.g. Gallium - Ga
Holes are the majority carriers.



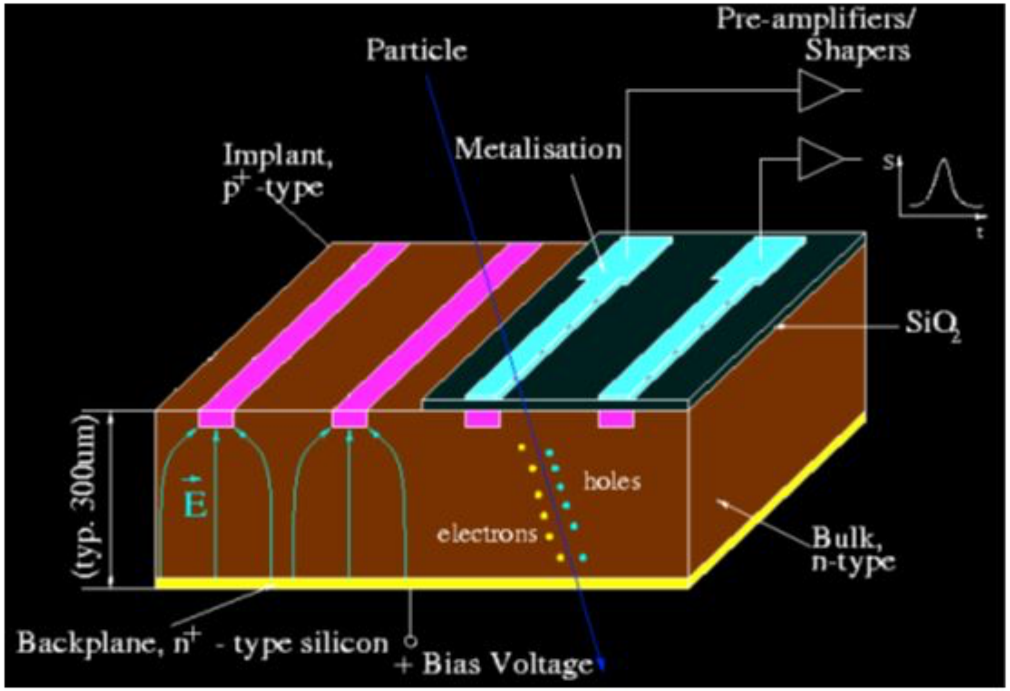




Doped semiconductor

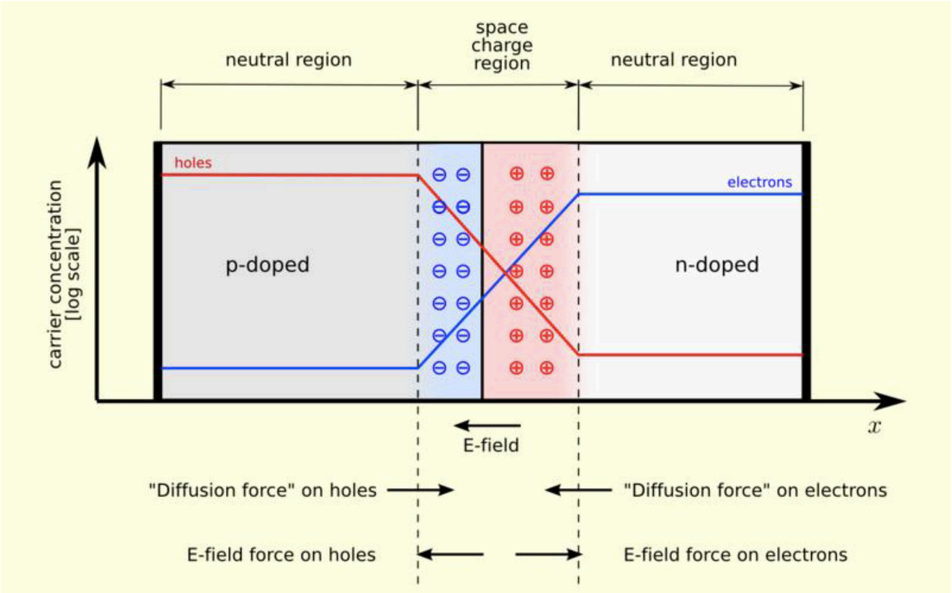


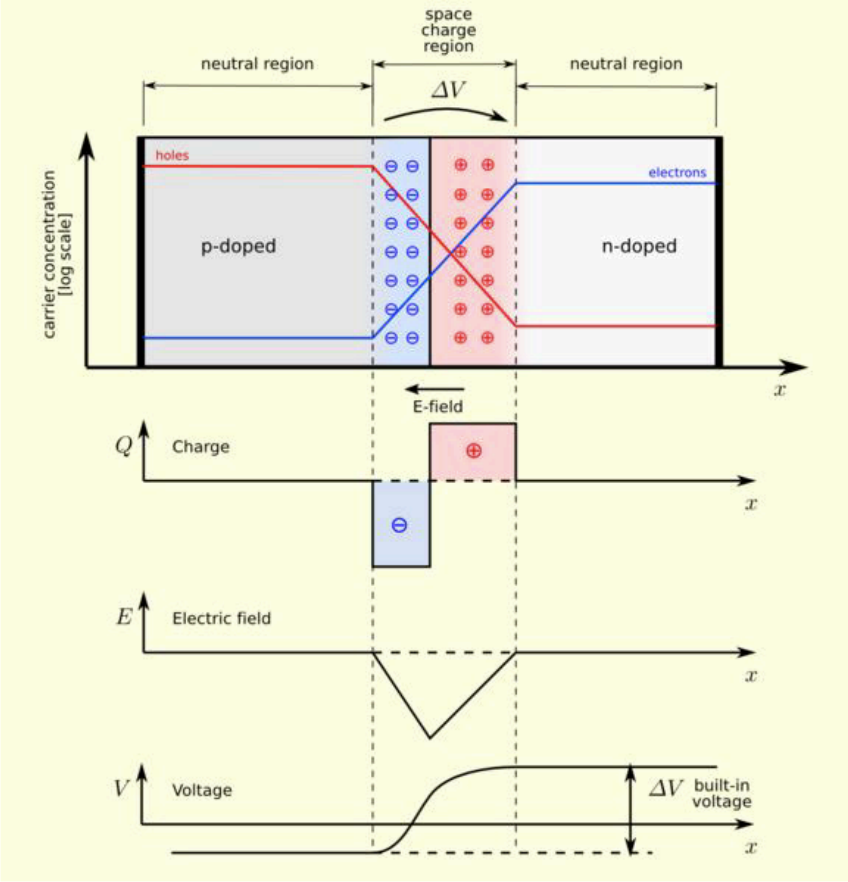
- A silicon detector is essentially a reverse biased diode.



Doped silicon: P-N Junction

PN junction without external voltage
– Free charges move until the chemical potential is balanced by an electrical potential called the built-in potential

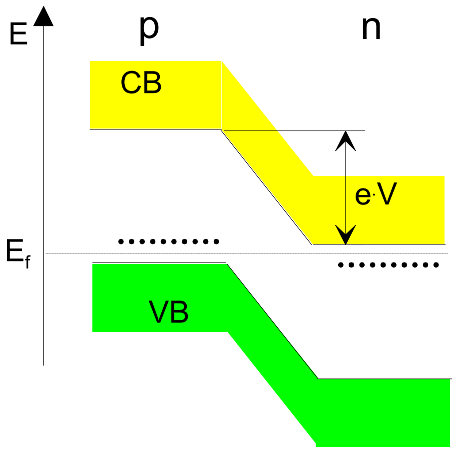


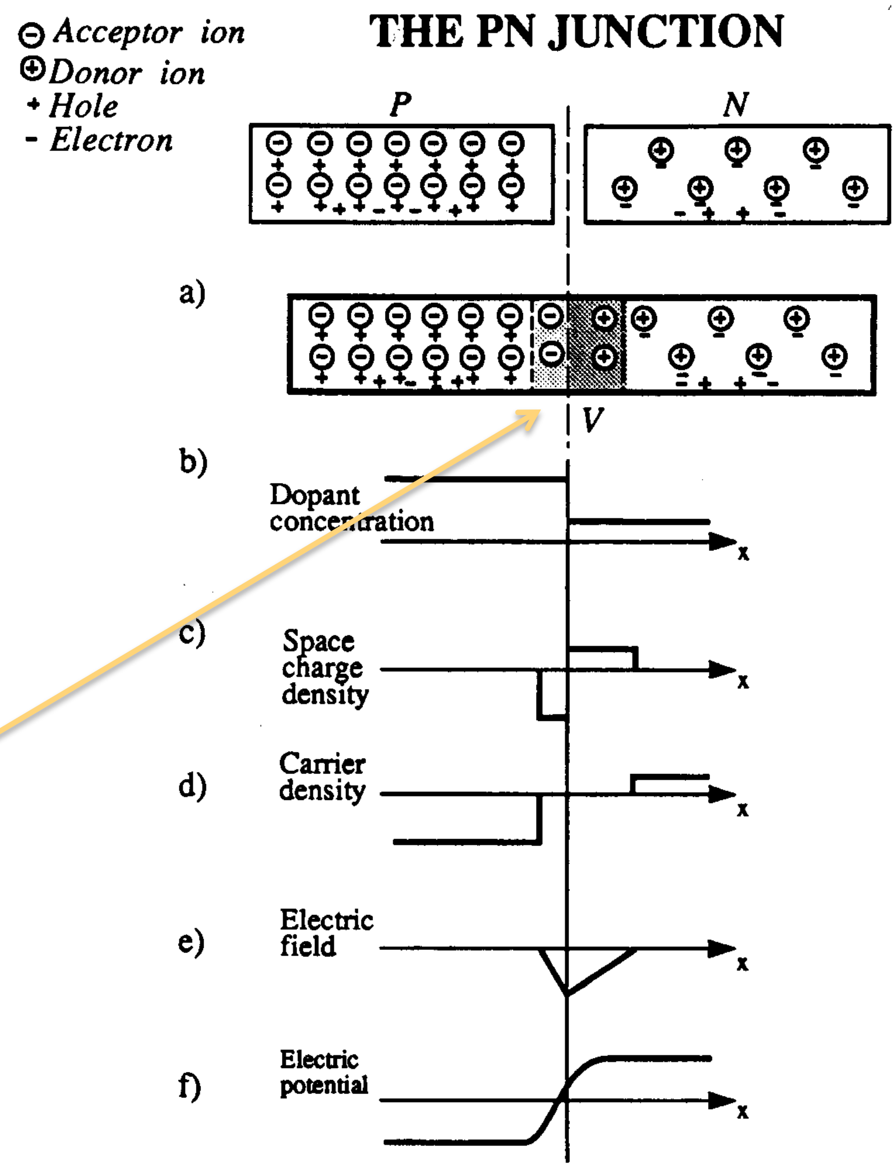


The space charge (depletion) region can be made bigger by applying a reverse bias voltage

There must be a single Fermi level !

Deformation of band structure → potential difference.





diffusion of e^- into p-zone, h^+ into n-zone

→ potential difference stopping diffusion

Silicon Strip Detectors

Segmented implant allows to reconstruct the position of the traversing particle in one dimension

•DC-coupled strip detector – simplest position sensitive Silicon detector

•Standard configuration:

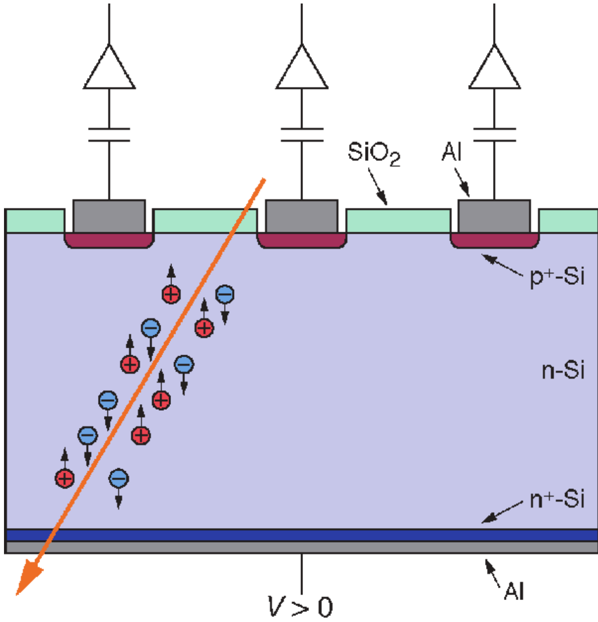
– **Strips p implants**

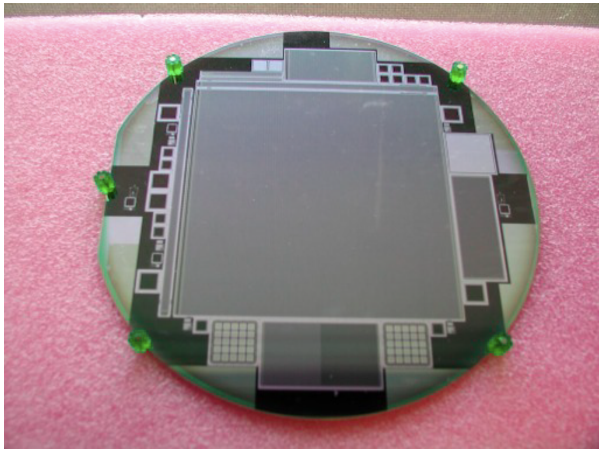
– Substrate n doped (~2-10 kΩcm) and ~300µm thick

– V dep< 200 V

– Backside Phosphorous implant to establish ohmic contact and to prevent early breakdown

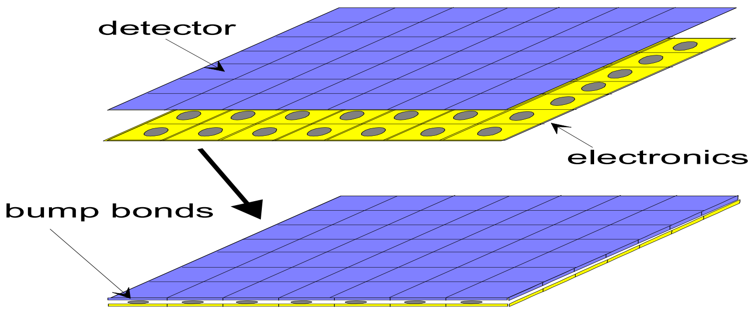
•Highest field close to the collecting electrodes (junction side) where most of the signal is induced



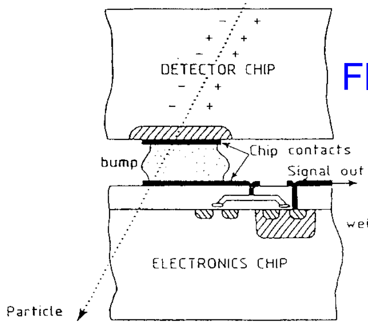


Silicon pixel detectors

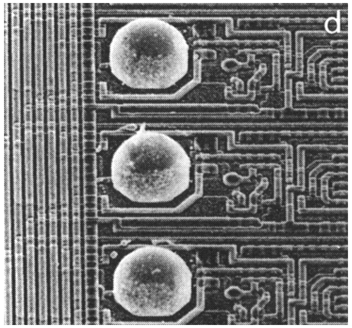
- **Silicon pixel detectors**
  - **Segment silicon to diode matrix**
  - **also readout electronic with same geometry**
  - **connection by bump bonding techniques**



RD 19, E. Heijne et al., NIM A 384 (1994) 399



Flip-chip technique



Pixel detector

Pixel detectors provides space-point information

<u>Advantages</u>

•Small pixel area

– low detector capacitance (≈1 fF/pixel)

– large signal-to-noise ratio (e.g. 150:1).

•Small pixel volume

– low leakage current (≈1 pA/pixel)

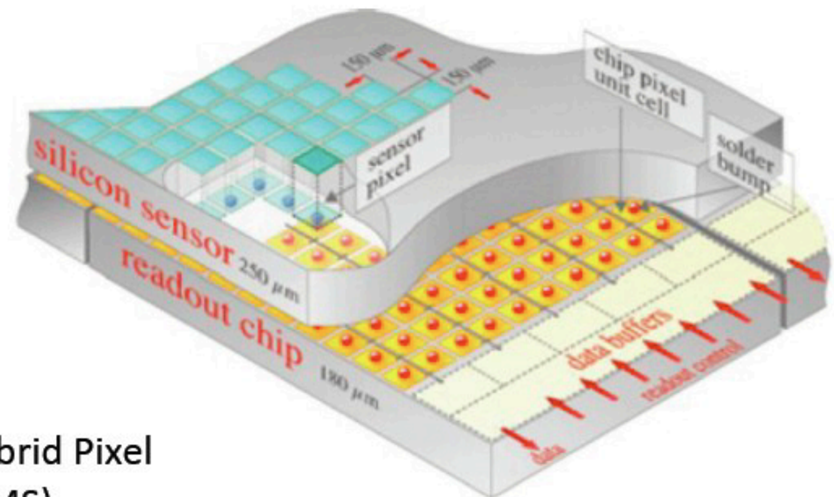
<u>Disadvantages</u>

•Large number of readout channels

•Large number of electrical connections

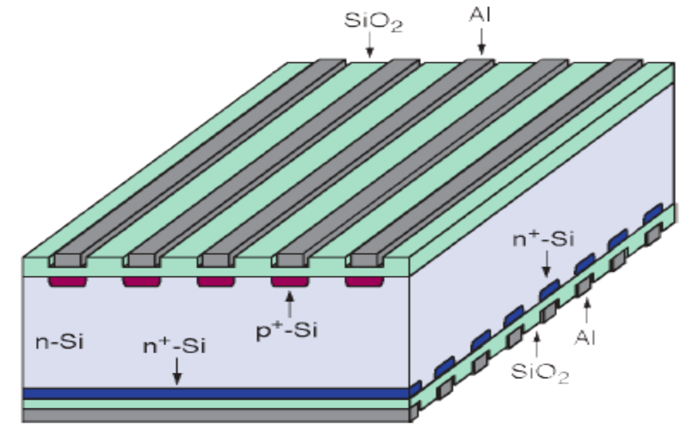
•Large data bandwidth

•Large power consumption

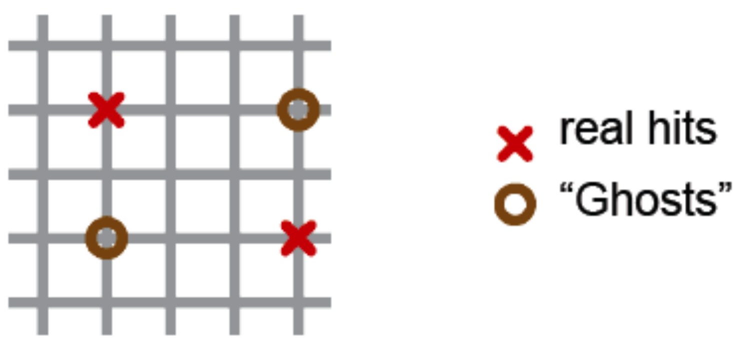


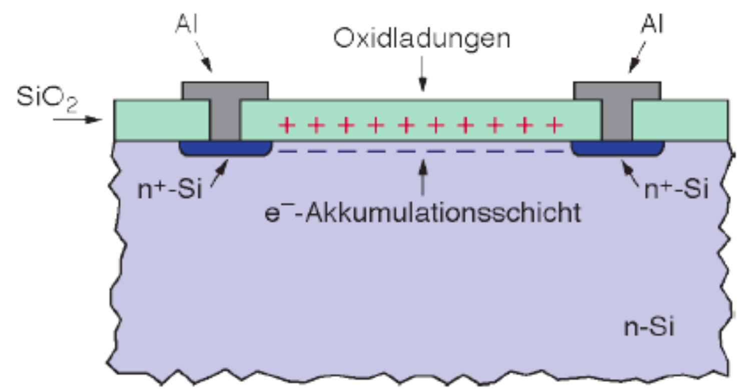
Hybrid Pixel
(CMS)

Double Sided Silicon Detectors



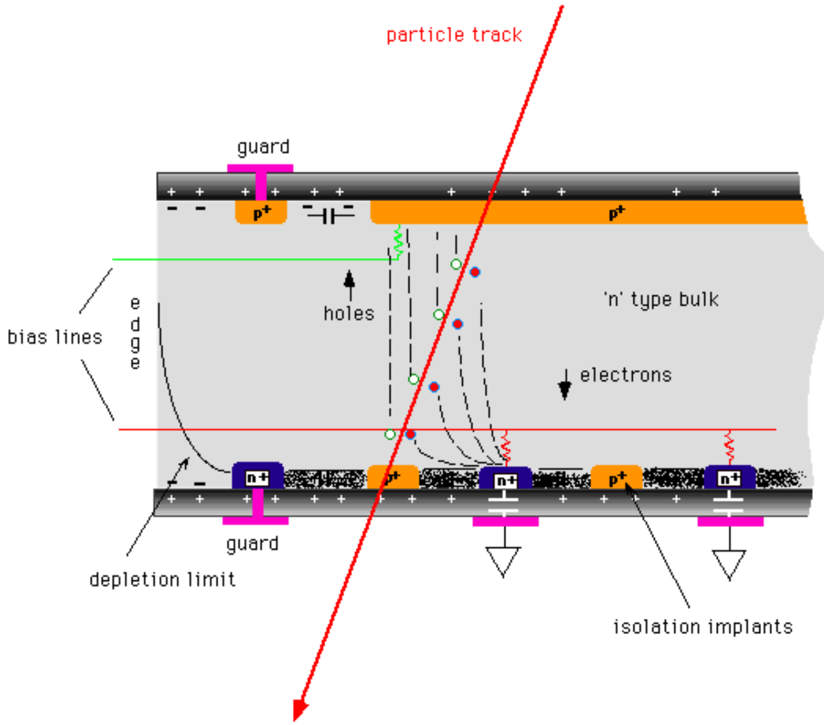
Scheme of a double sided strip detector
(biasing structures not shown)

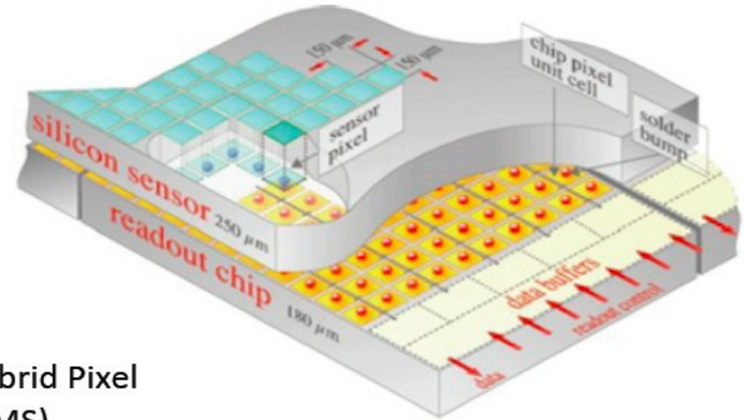




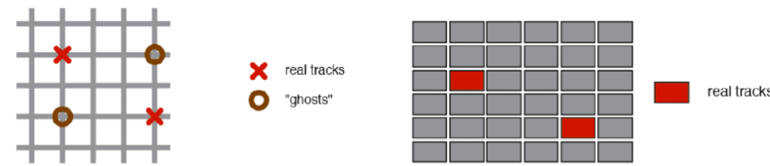
Positive oxide charges cause electron accumulation layer.

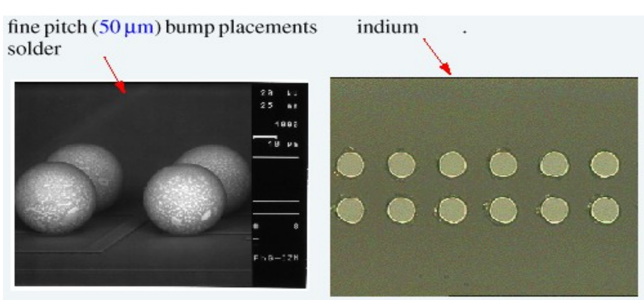
Pixel detector

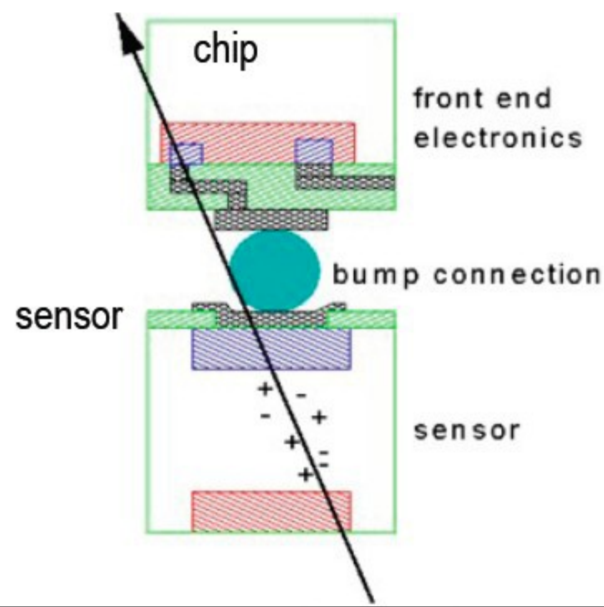




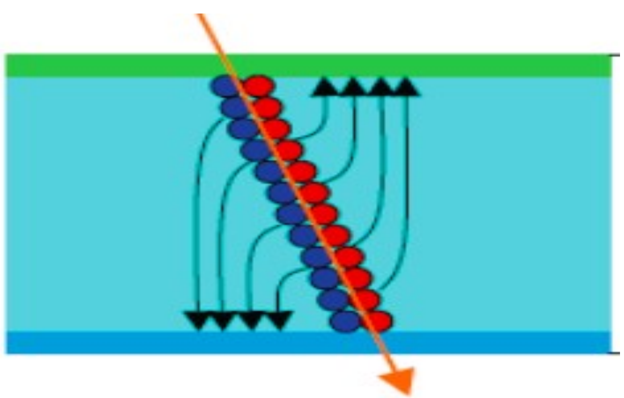
Hybrid Pixel
(CMS)

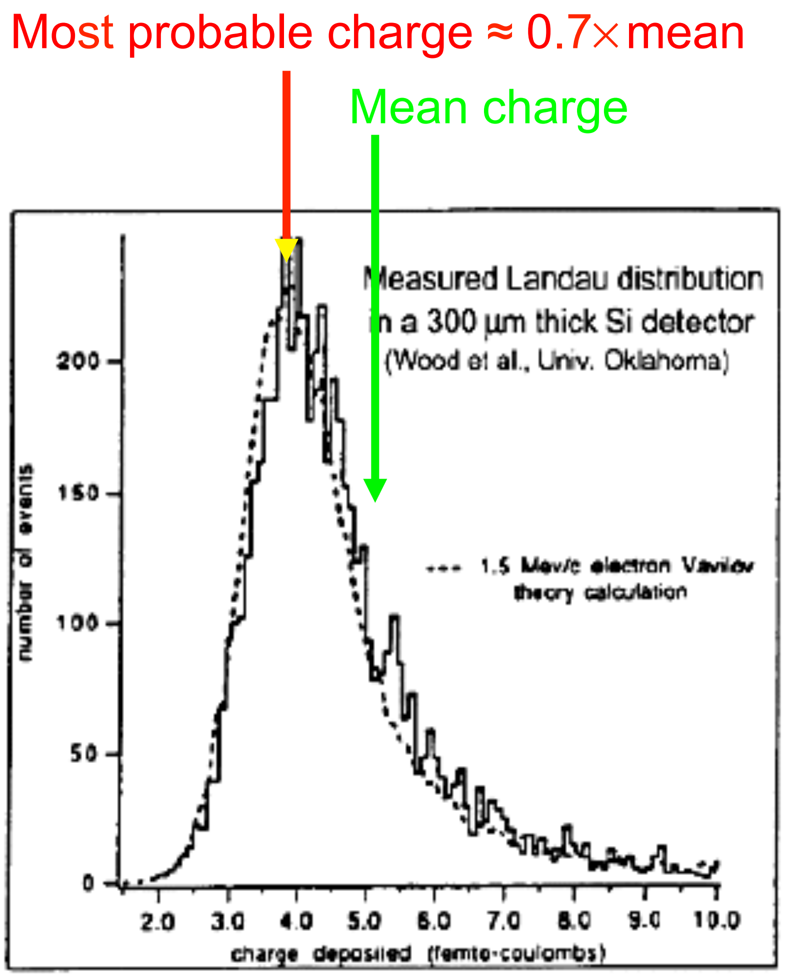




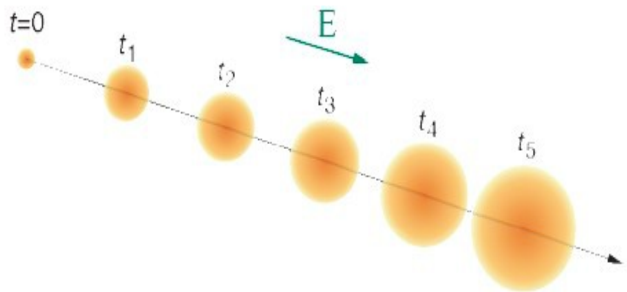


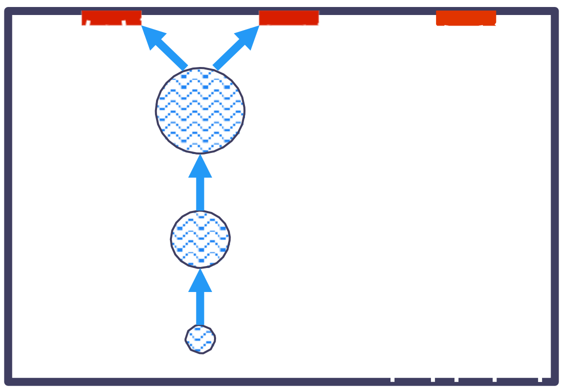
https://www.youtube.com/watch?v=ojeVwQxOrGo&feature=youtu.be



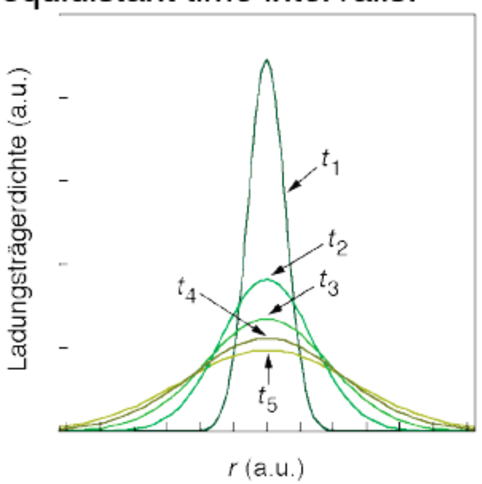

Most probable charge ≈ 0.7×mean
Mean charge
Measured Landau distribution
in a 300 µm thick Si detector
(Wood et al., Univ. Oklahoma)
1.5 Mev/c electron Vavilov theory calculation
number of events
0
50
100
150
200
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
charge deposited (femto-coulombs)

Diffusion



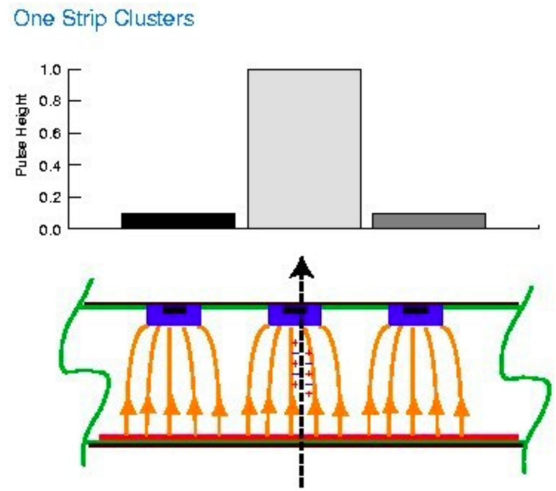


Charge density distribution for 5 equidistant time intervalls:

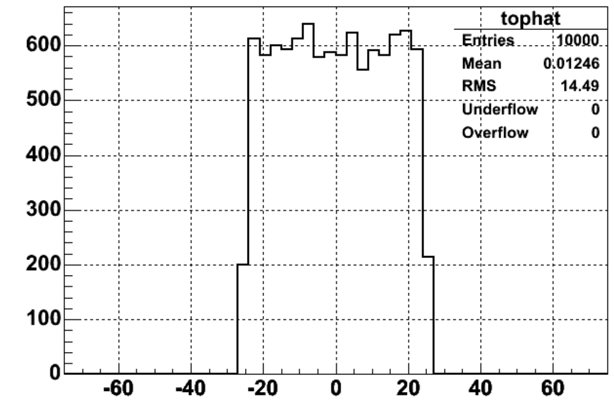


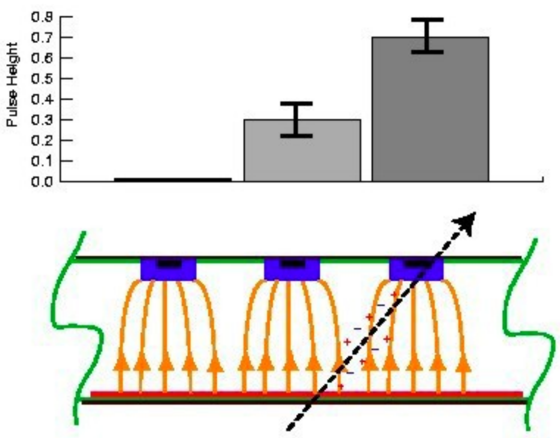
Position resolution

One strip clusters



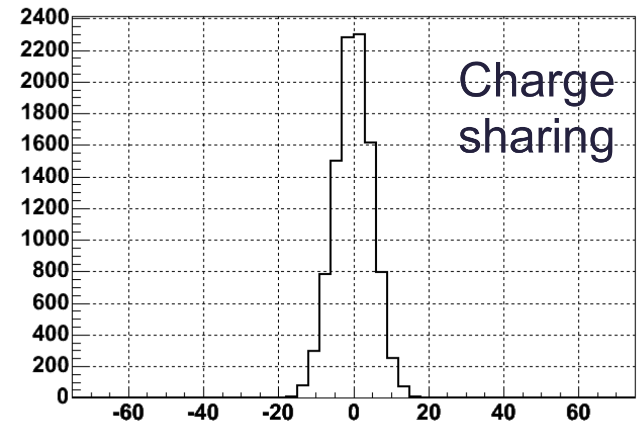
$$\sigma = \frac{pitch}{\sqrt{12}}$$



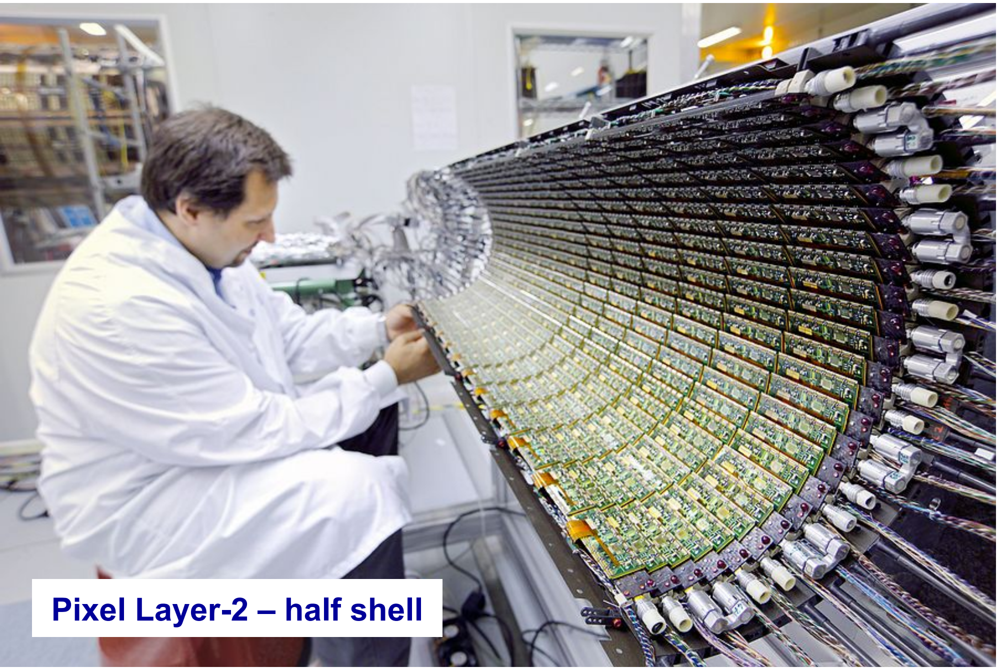


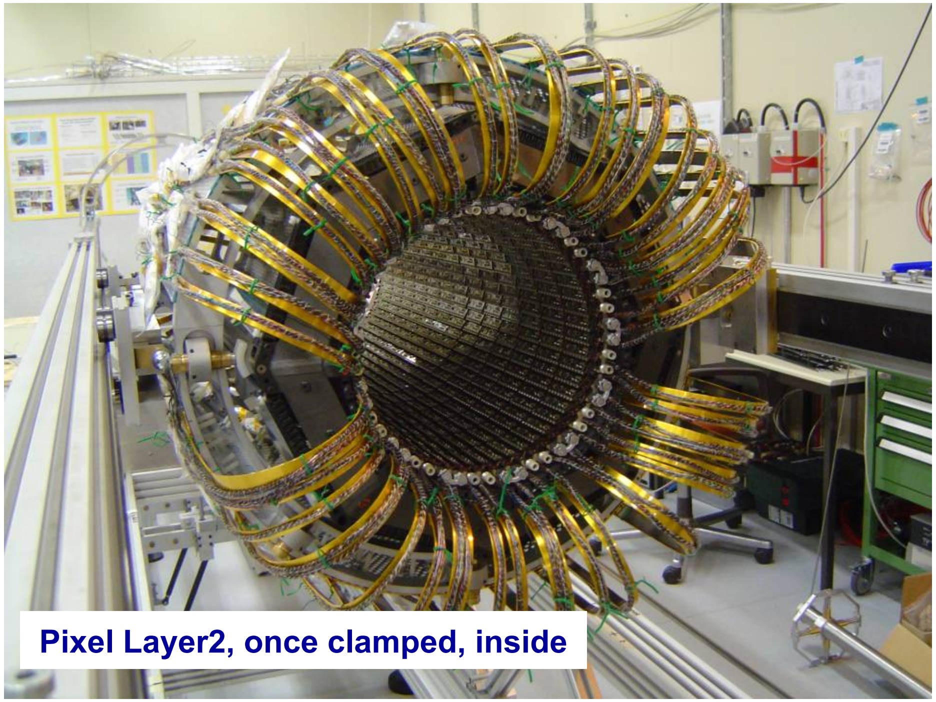
$$\sigma \approx \frac{pitch}{1.5 \cdot \sqrt{12}}$$

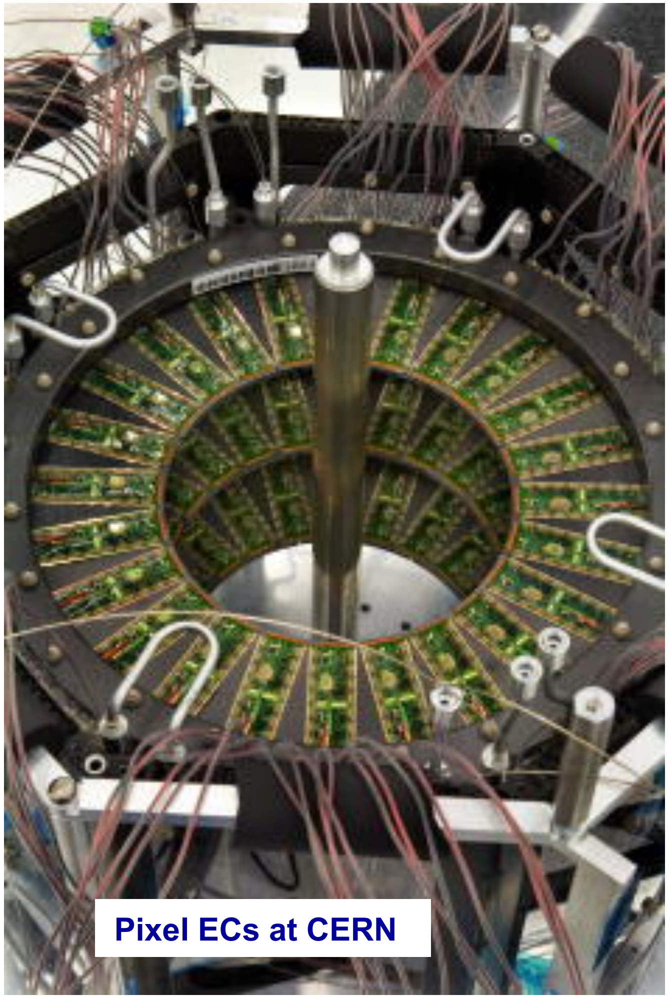
$$\eta = \frac{PH_R}{PH_L + PH_R}$$

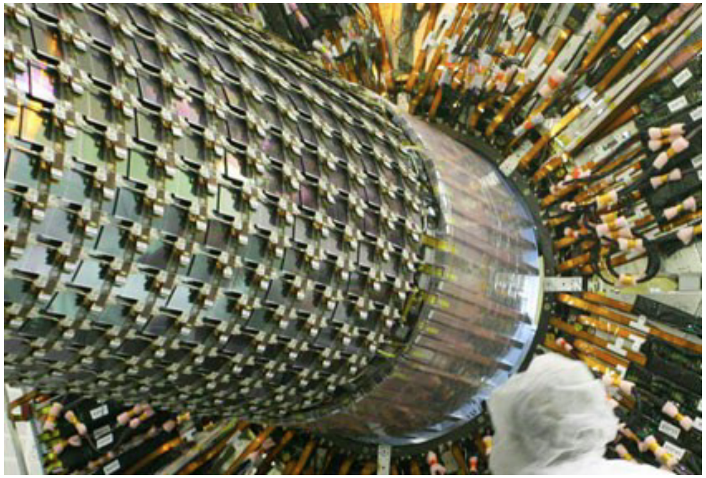


Lot of progress on the Pixels!

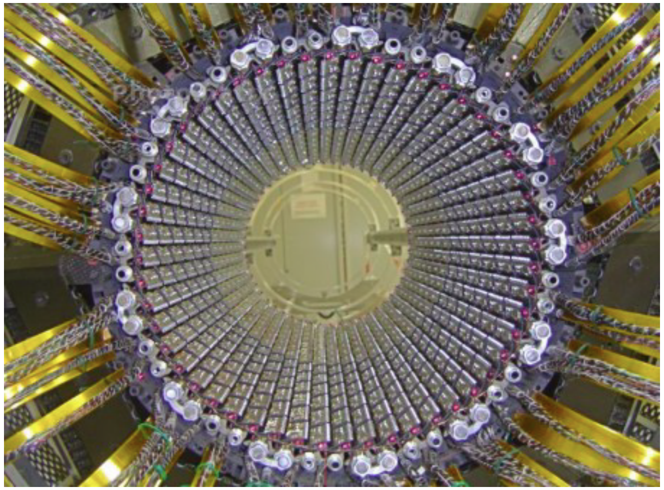

Pixel Layer-2 – half shell


Pixel Layer2, once clamped, inside

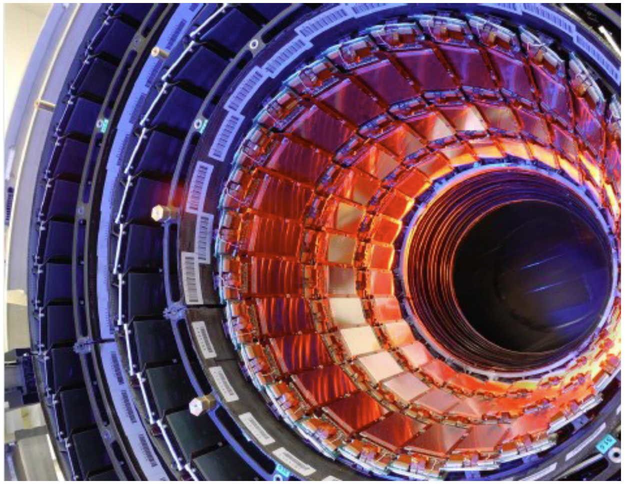

Pixel ECs at CERN



ATLAS SCT Strip Detector



ATLAS Pixel detector



CMS Strip Detector