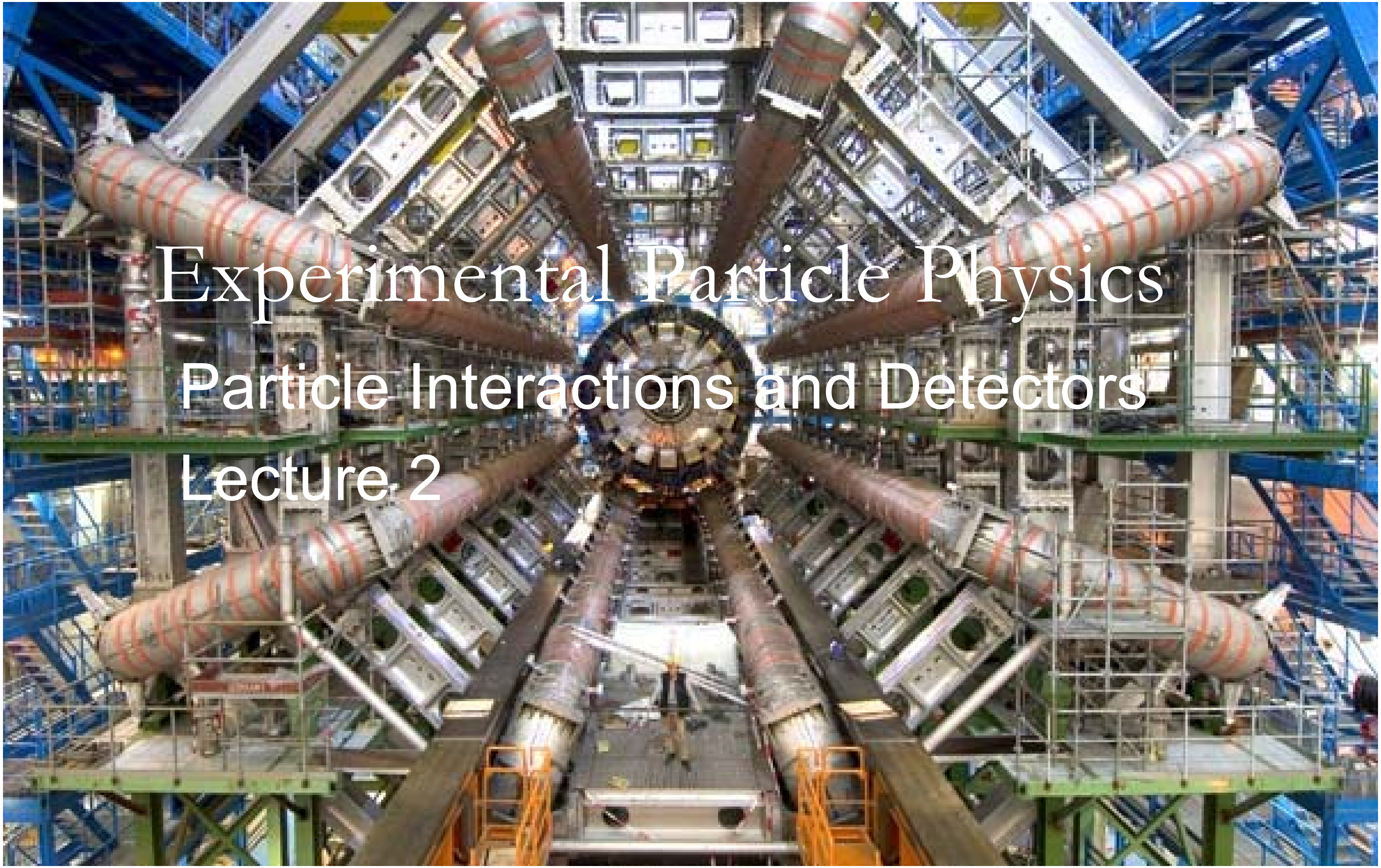


Experimental Particle Physics

Particle Interactions and Detectors

Lecture 2

How do we detect Particles?

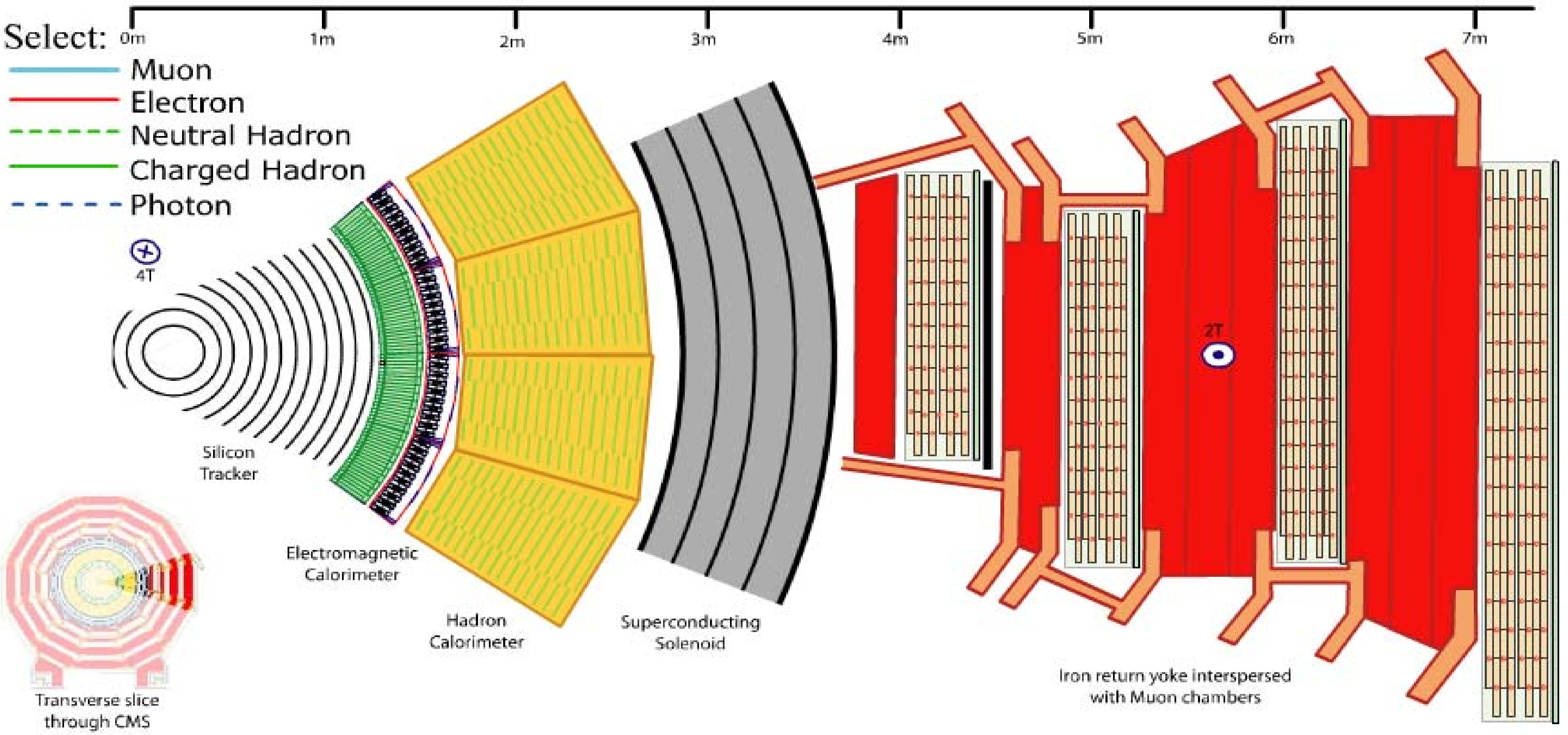
- Particle Types
  - Charged ($e^-/K^-/\pi^-$)
  - Photons (γ)
  - Electromagnetic (e^-)
  - Hadronic ($K^-/\pi^-/\mu^-$)
  - Muonic (μ^-)
  - Gravitons !
- Interaction with matter
  - Ionisation Loss
  - Radiation Loss
  - Photon Absorption
  - Electromagnetic Showers
  - Hadronic Showers
  - Cherenkov Radiation
  - Transition Radiation

In general, we measure the energy lost as the particle passes through a medium.

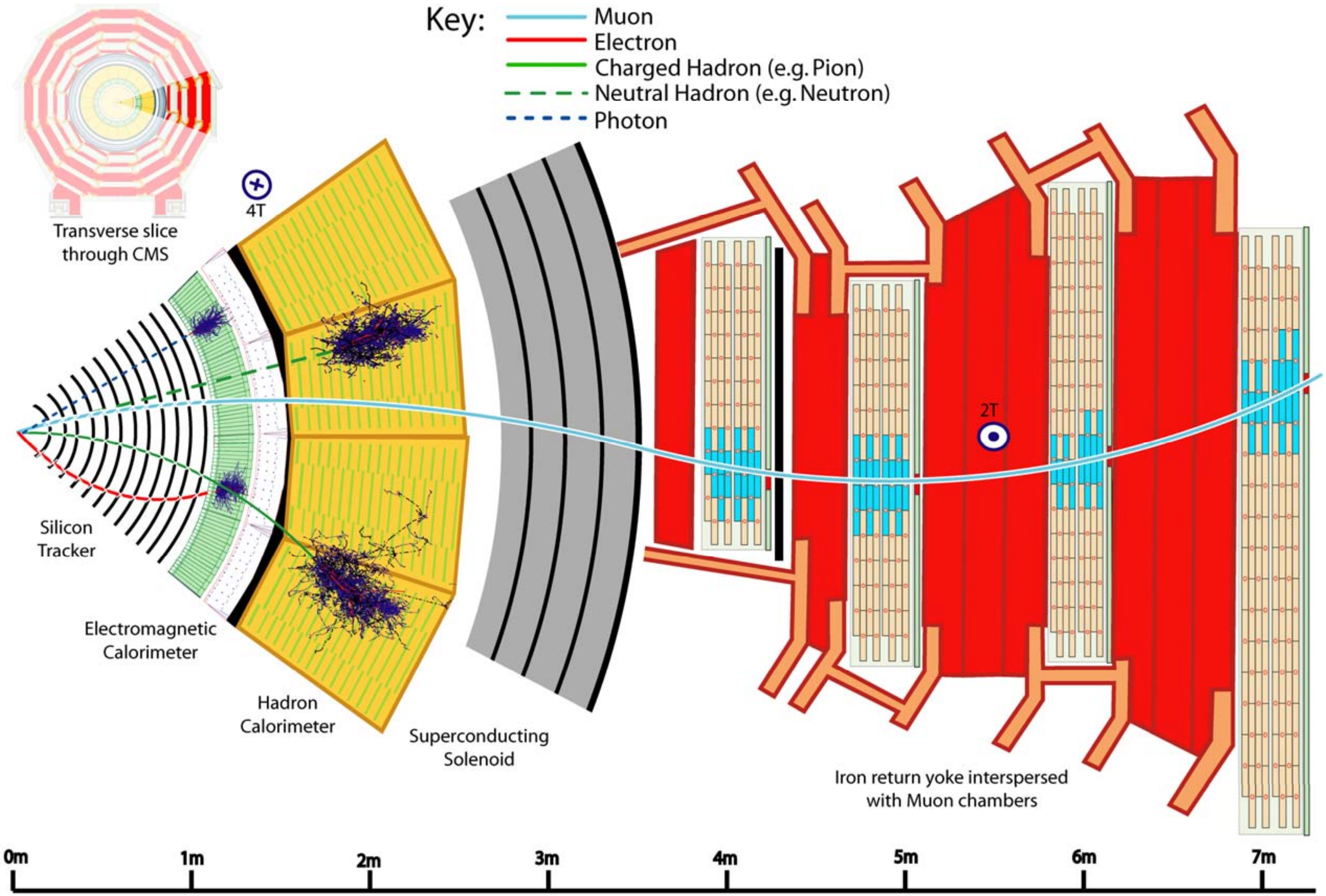
Transverse slice through CMS detector

Click on a particle type to visualise that particle in CMS

Press “escape” to exit



D. Barney, CERN, 2004


Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
Transverse slice through CMS
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0m
1m
2m
3m
4m
5m
6m
7m

Which particles interact with which subdetector?

(caveat: some particles leave a small signal in a subdetector e.g. muon in EM calorimeter)

Detector	Electron	Charged Hadron (K^+/π^+)	Muon	Neutral Hadron (π^0)	Photon
Tracking	Yes	Yes	Yes		
Cherenkov		Yes			
Transition Radiation	Yes	Yes			
EM Calorimeter	Yes				Yes
Hadronic Calorimeter		Yes		Yes	
Muon Detector			Yes		

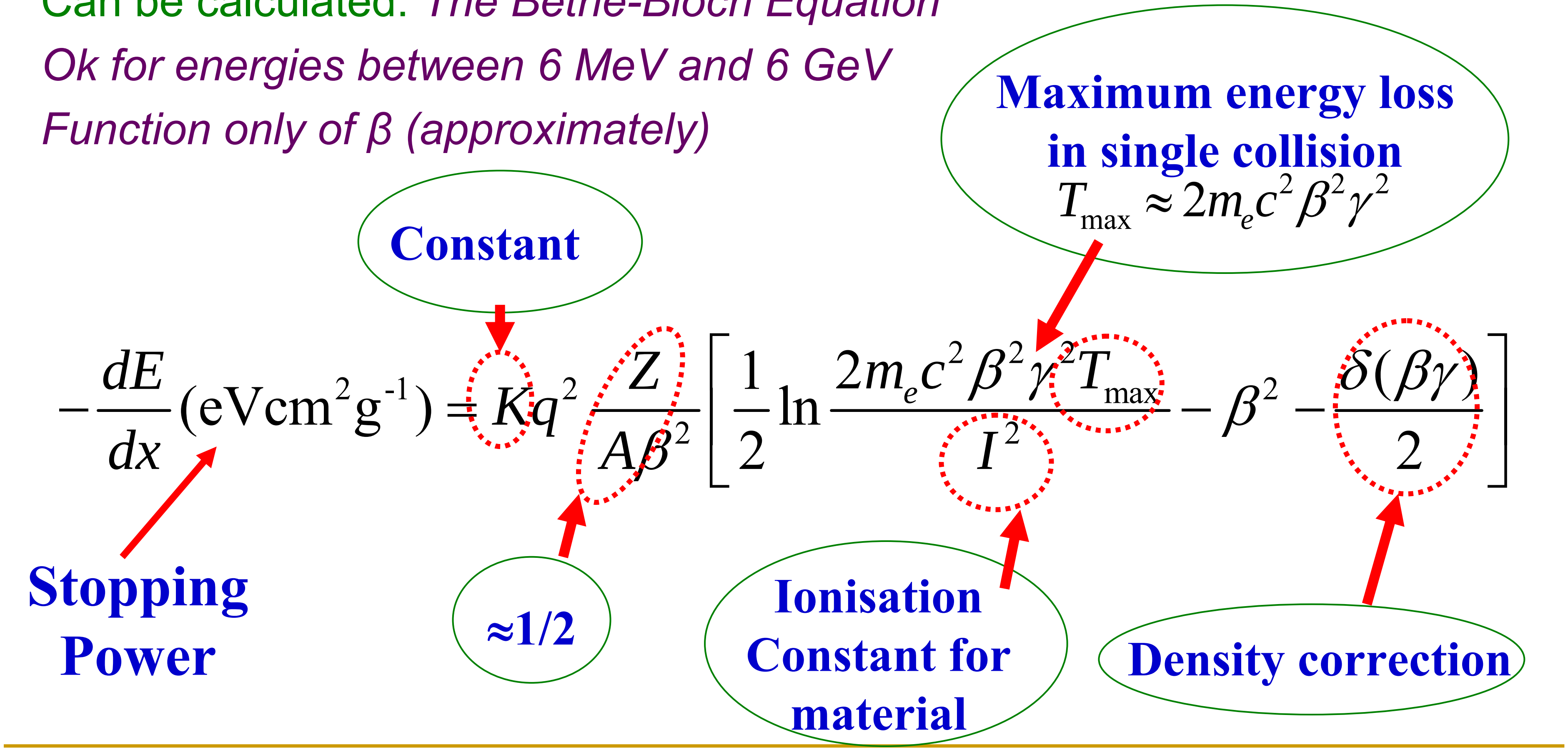
Charged Particle Detectors

- Physics
  - Ionisation
  - Mean Energy Loss
  - Fluctuations
  - Cherenkov Light
  - Transition Radiation

- Detectors
  1. Emulsion
  2. Bubble Chambers
  3. Scintillation Detectors
  4. Wire Chambers
  5. Multi Wire Proportional Chambers (MWPC)
  6. Geiger Muller
  7. Solid State Devices
  8. Time Projection (TPC)
  9. Resistive Plate Counters (RPC)
  10. Limited Streamer Tubes (LST)
  11. Cherenkov
  12. Transition Radiation (TRD)

Ionisation and Atomic Excitation

- Heavy Charged particles interact with electrons in material as they pass
- Can be calculated: *The Bethe-Bloch Equation*
- *Ok for energies between 6 MeV and 6 GeV*
- *Function only of β (approximately)*



Maximum energy loss in single collision

$T_{\max} \approx 2m_ec^2\beta^2\gamma^2$

Constant

$$-\frac{dE}{dx}(\mathrm{eVcm^2g^{-1}}) = Kq^2\frac{Z}{A\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2}-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

Stopping Power

≈1/2

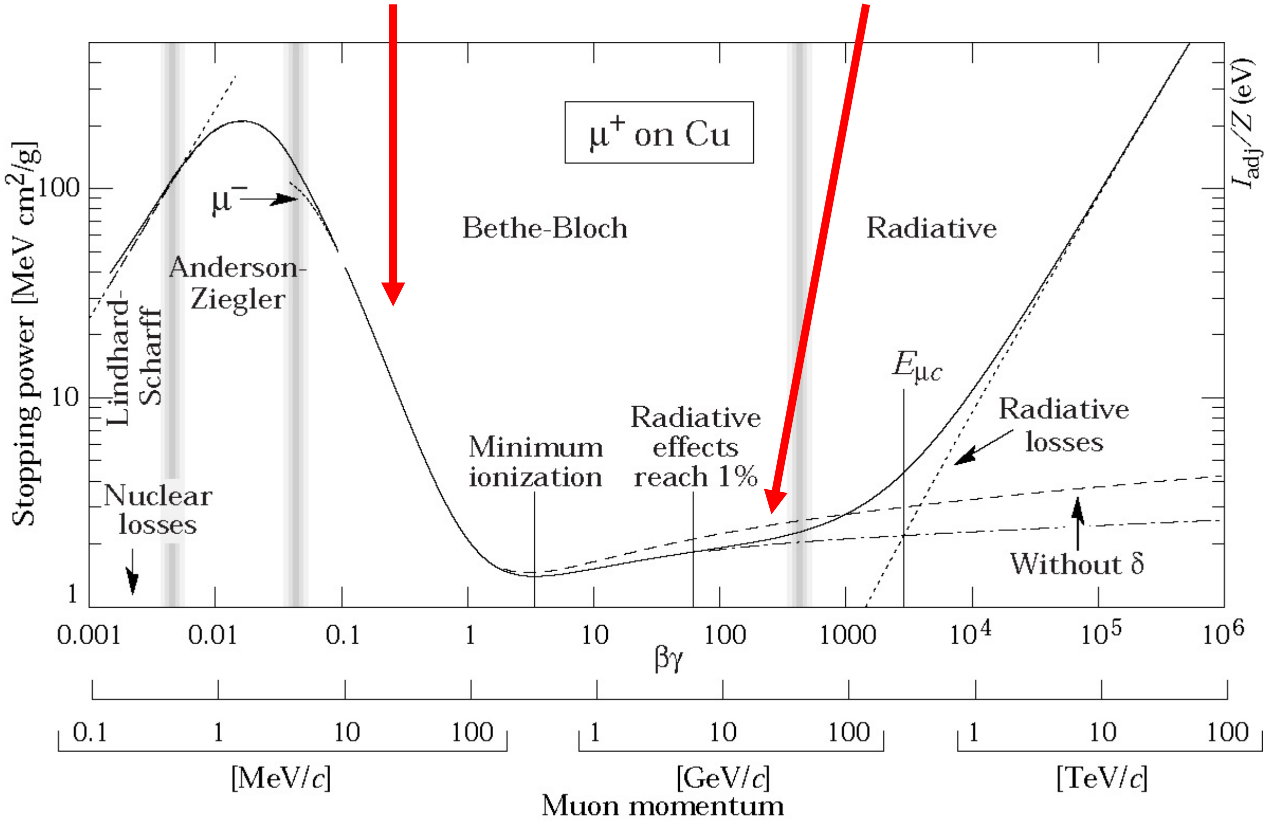
Ionisation Constant for material

Density correction

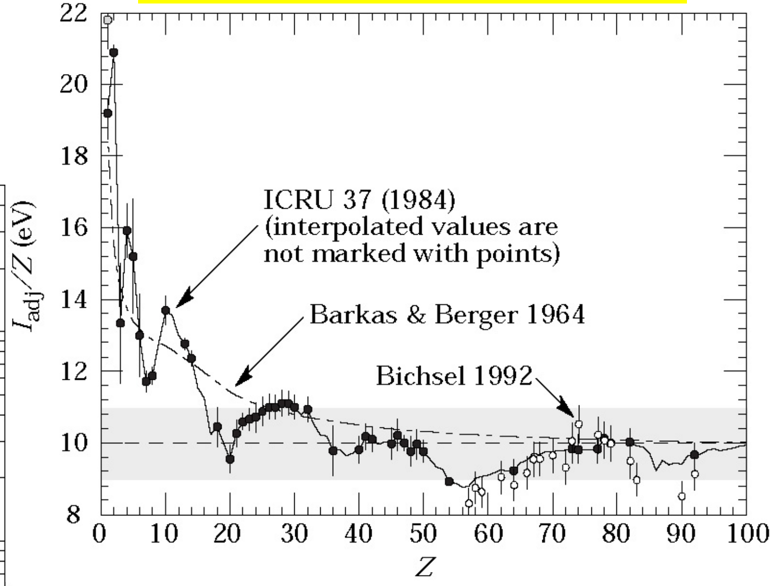
Stopping Power

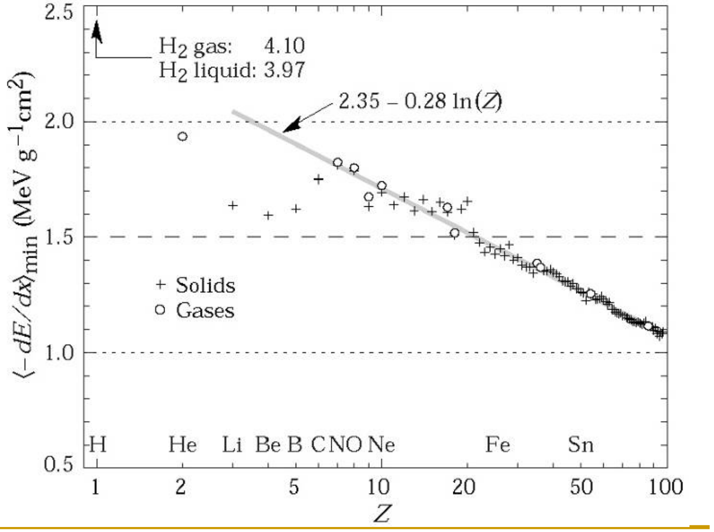
$1/\beta^2$

$\ln(\beta^2)$

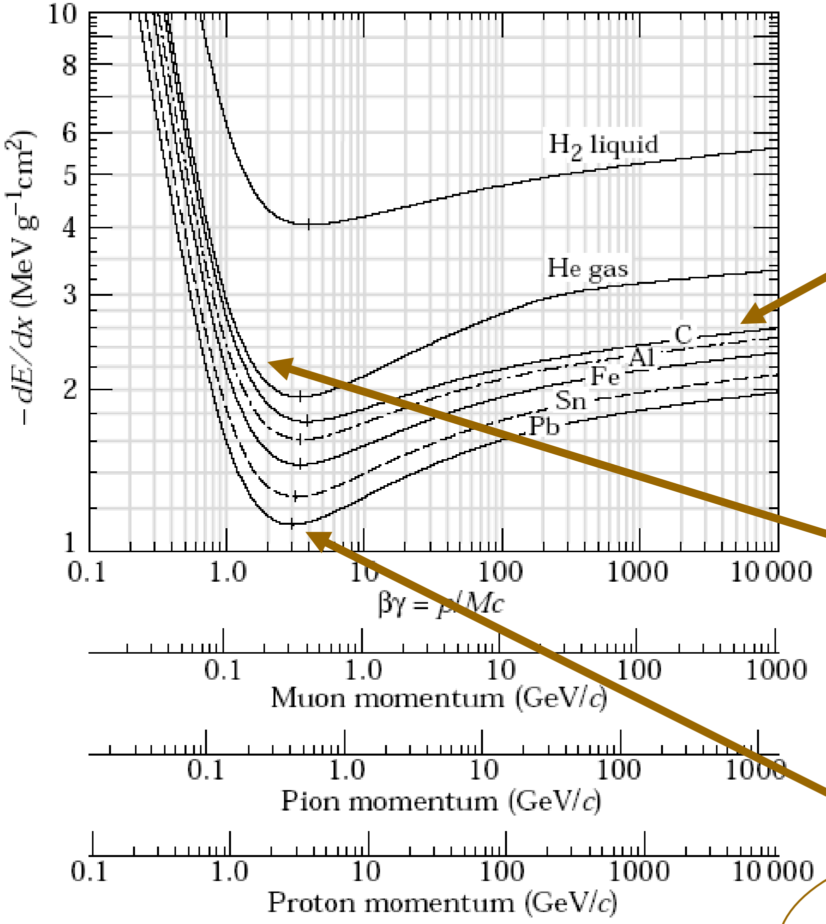


Ionisation Constant





Mean Energy Loss in different materials



High energy
~ ln γ

$$-\frac{dE}{dx} \approx Kq^2 \frac{Z}{A\beta^2}\left[\ln \frac{2m_e c^2 \beta^2 \gamma^2}{I^2} - \beta^2\right]$$

Low energy
~ 1/β²

Minimum at
γ≈3

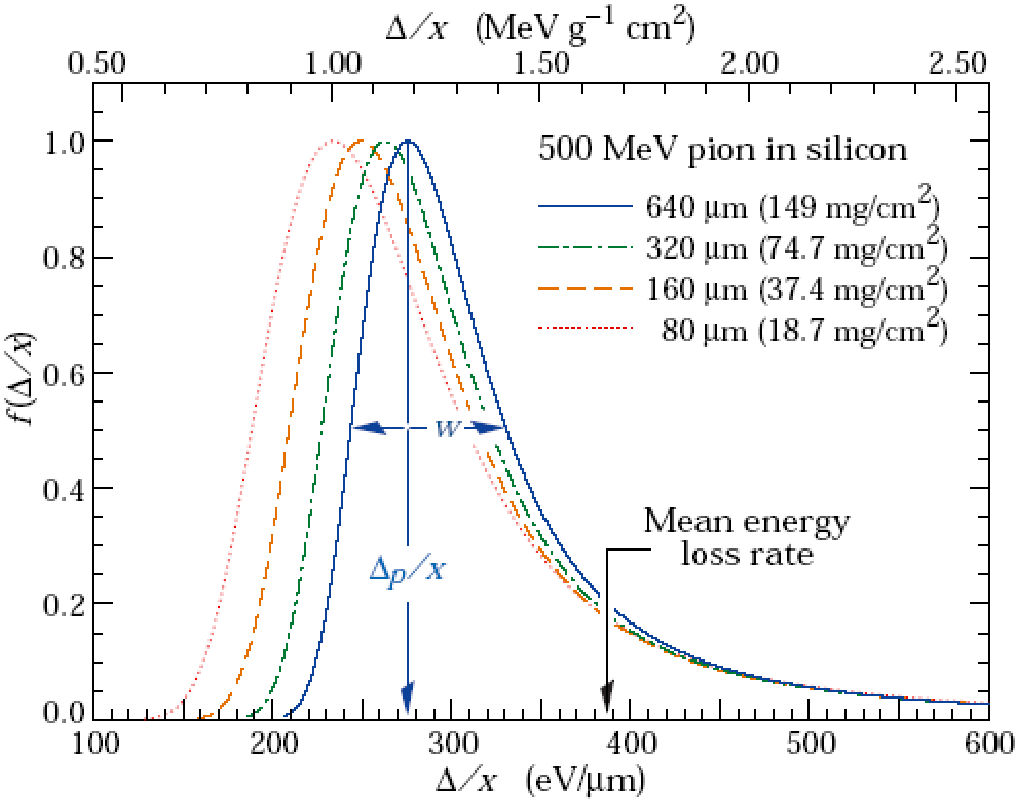
Distance units:

- **$g\ cm^{-2}$**

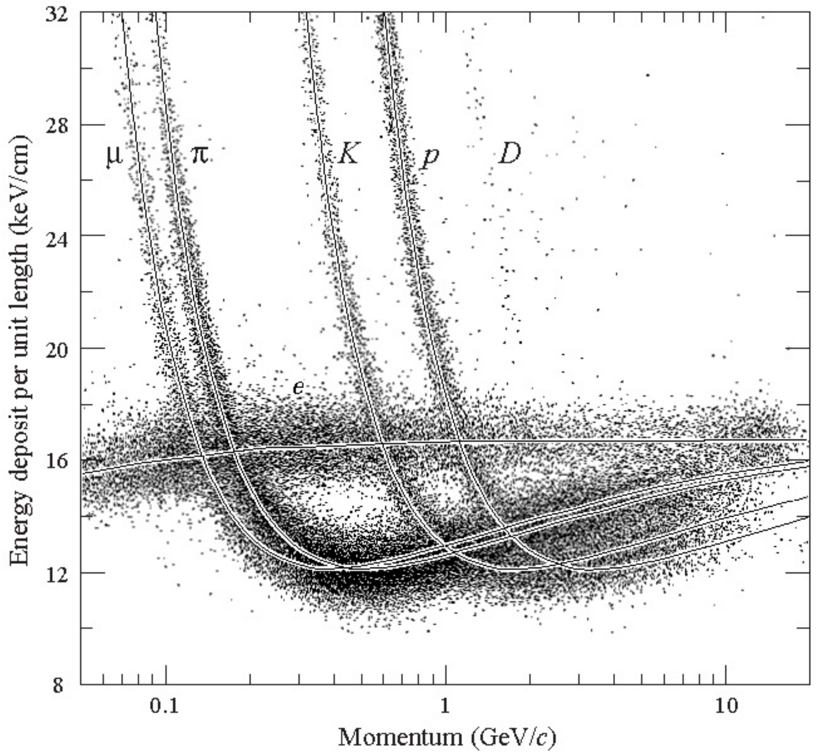
Energy Fluctuations

- Bethe-Block only gives mean, *not* most probable
- Large high energy tail – δ rays
- Landau distribution:

δ-rays : electrons produced by the Bethe-Block equation that have sufficient energy to ionize further atoms through subsequent interactions on their own.

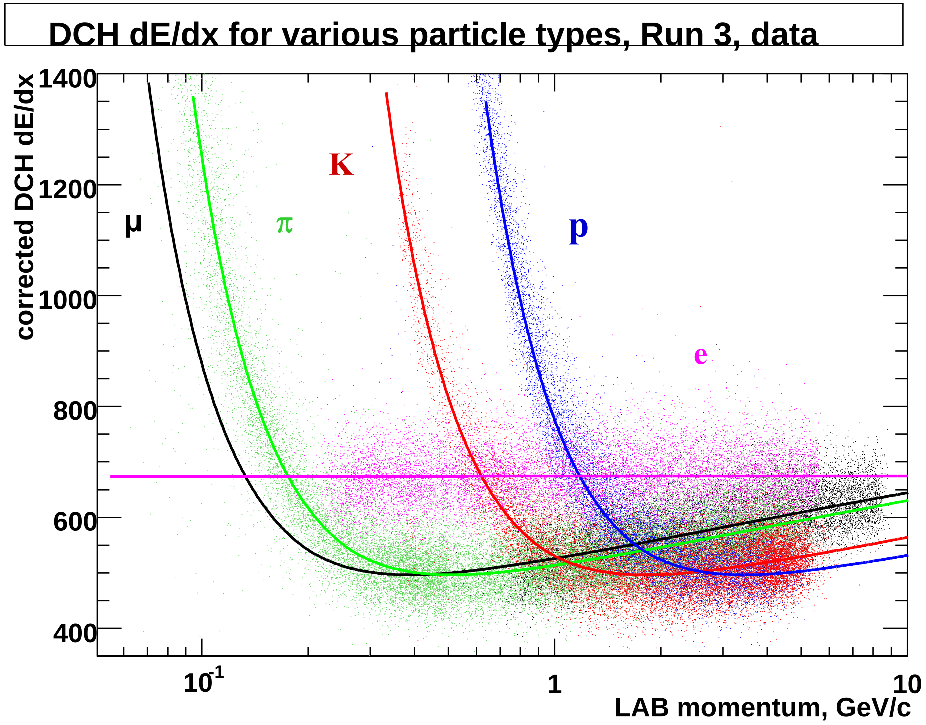


Particle Identification by Energy Loss (dE/dx)



Results from a Time Projection Chamber

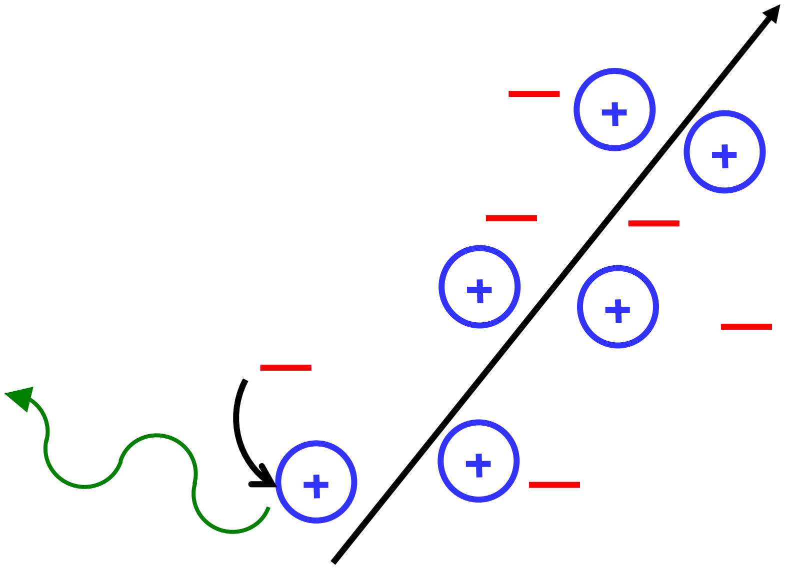
(PEP4/9)



Results from a Drift Chamber

(BaBar)

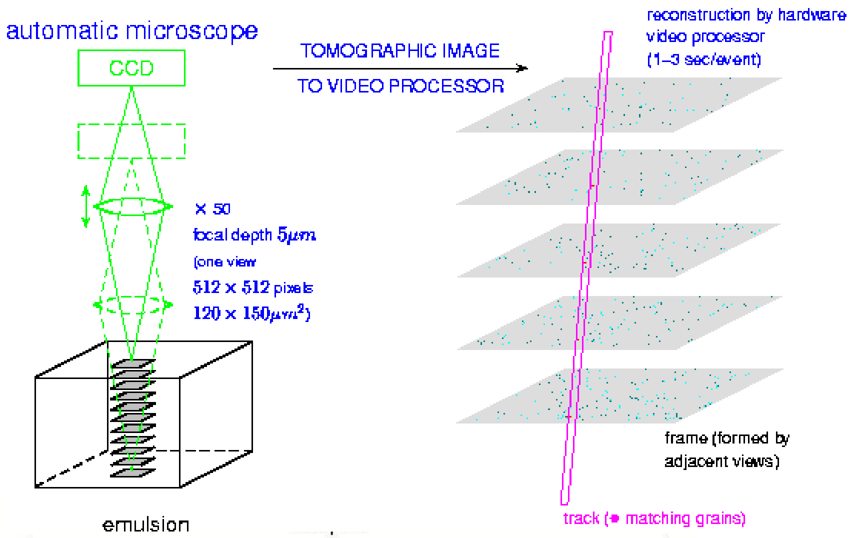
Ionisation Detectors

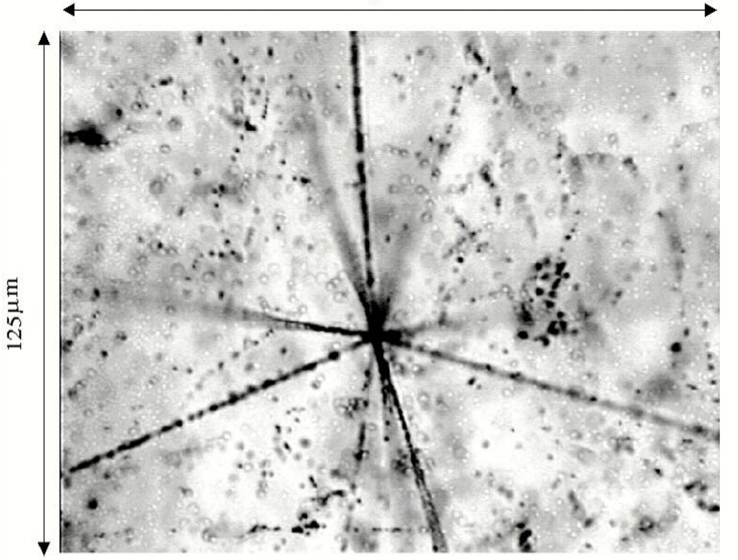


Ionisation used to detect particles in different ways:

1. Observe physical or chemical change due to ions
2. Detect energy from recombination - scintillation
3. Collect and measure free charges - electronic

Emulsions





- Expose film to particles and develop
- Natural radioactivity was discovered this way
- Still occasionally used for very high precision, low rate experiments
- Similar technique in etched plastics

CHORUS (neutrinos)

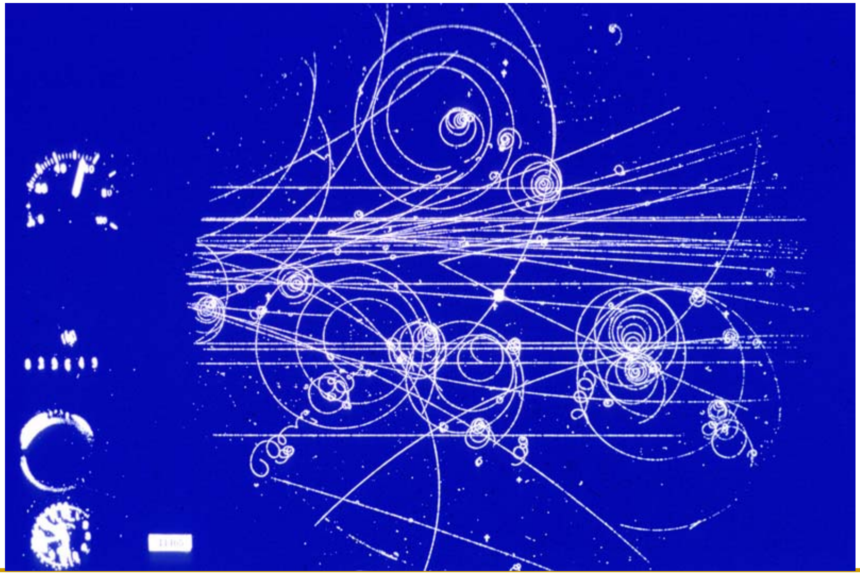
800kg of emulsion

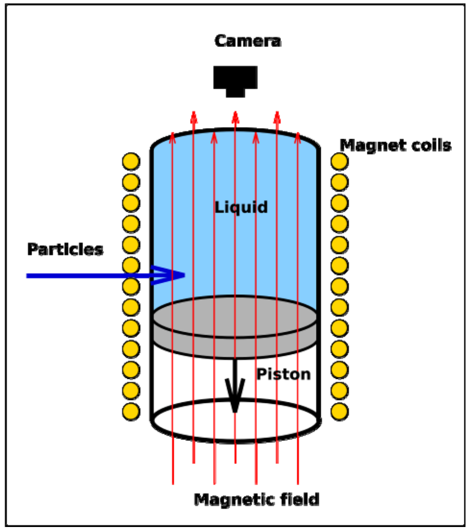
4 stacks of 8 modules each 35 x 70 x 2.9 cm^3

Bubble Chambers (1960s-1970s)

- Ionisation trail nucleates bubbles in superheated liquid
- Liquid H_2 (or similar) close to boiling point
- Suddenly reduce pressure.
- Fire beam into chamber
- Take photo
- Cloud chamber similar: ions nucleate condensation in saturated vapour

BEBC

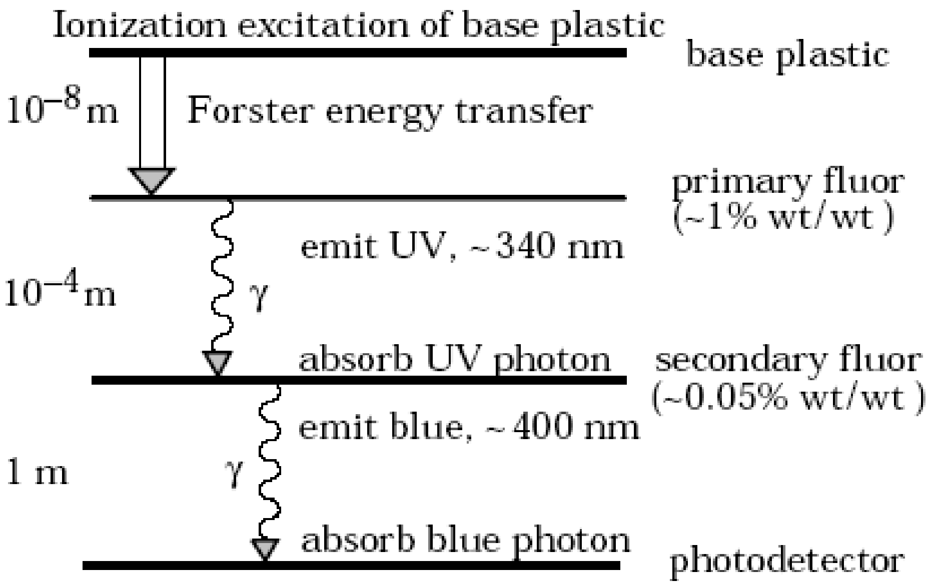


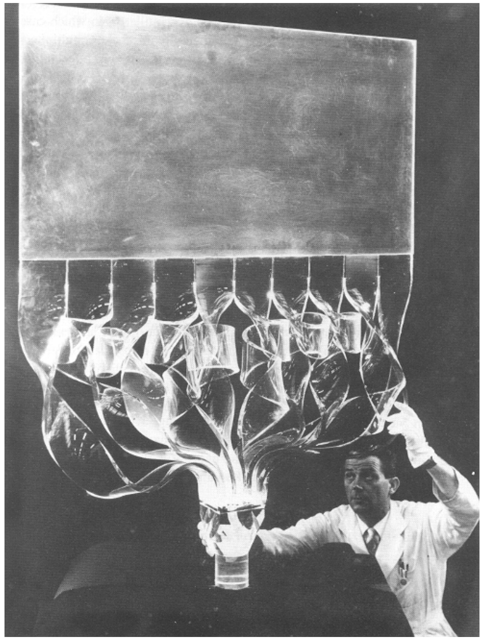


Scintillation Detectors

Detect photons from electronic recombination of ions

- Organic (plastic)
- Inorganic (crystal or glass)
    - doping normally required

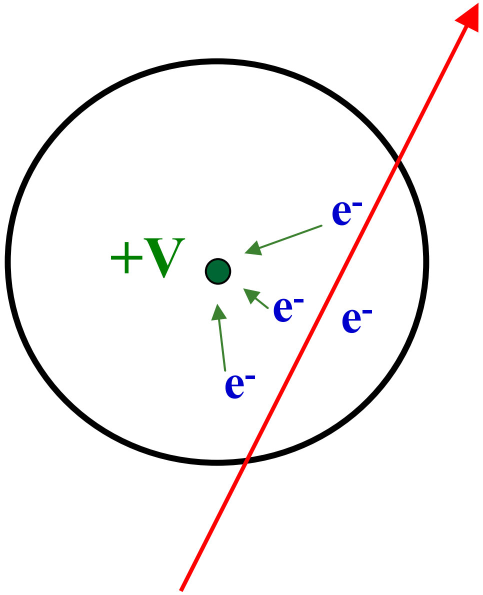


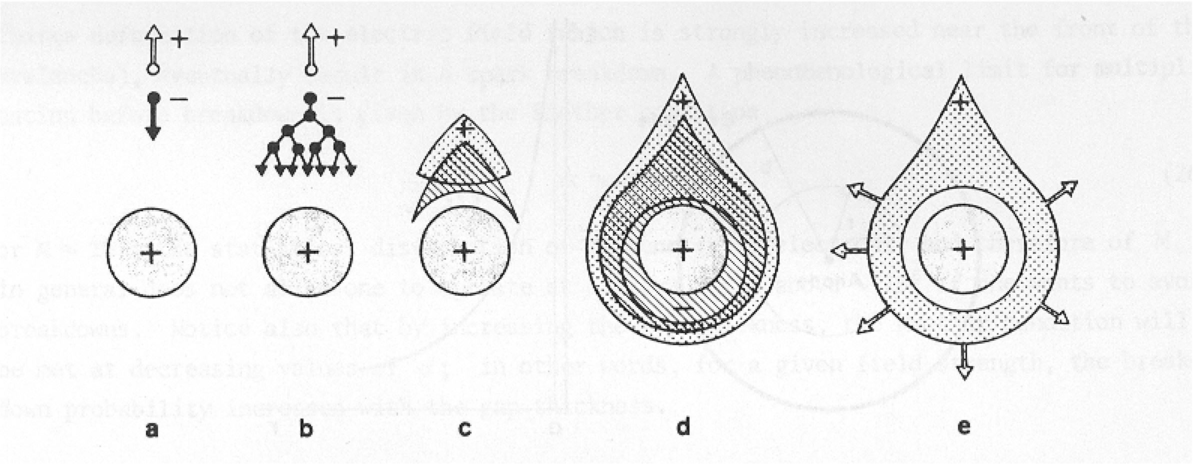


- Not very efficient ~1 photon/100eV
- Light carried to sensitive photodetectors
- Fast, cheap and flexible

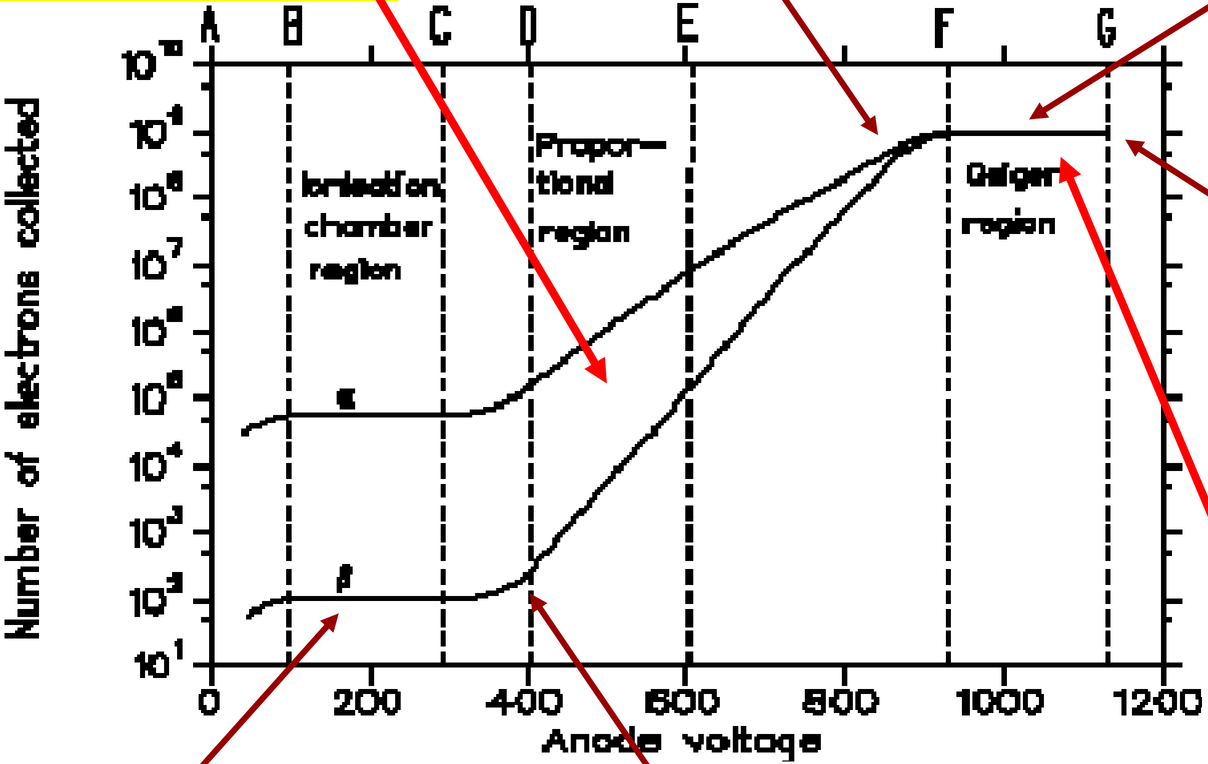
Wire Chambers

- Free electrons will be attracted to anode
- Electric field near thin wire increases
- Secondary ionisation may start to occur
  - *avalanche!*
- *A typical gas detector will have ~20 primary ions per cm created by a track.*





Gas Amplification



Proportional Chambers

Maximum gain ~10^7

Avalanche fills volume

Arcing

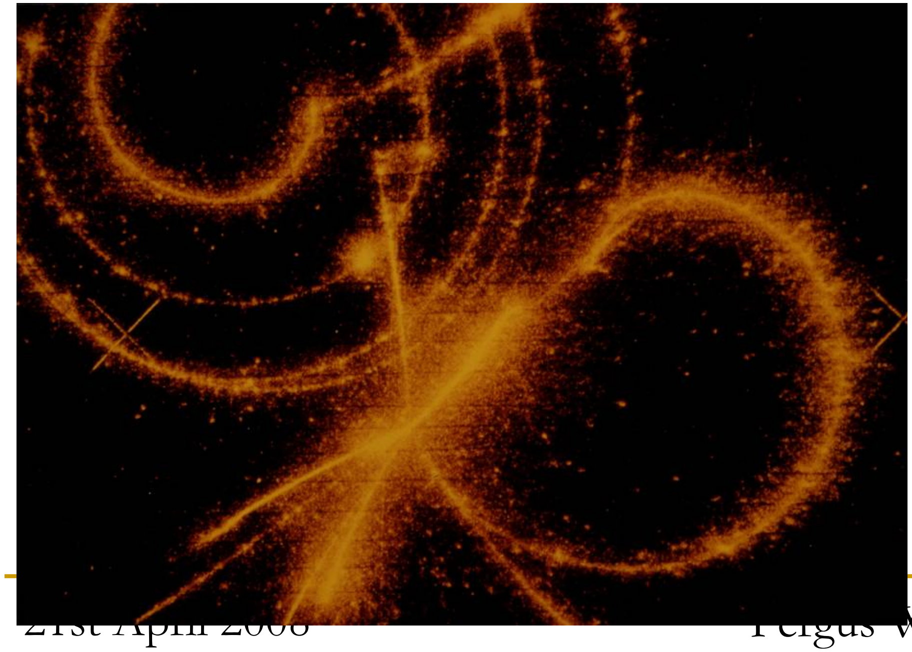
- **Geiger Muller Tube**
- **Resistive Plate Chambers**

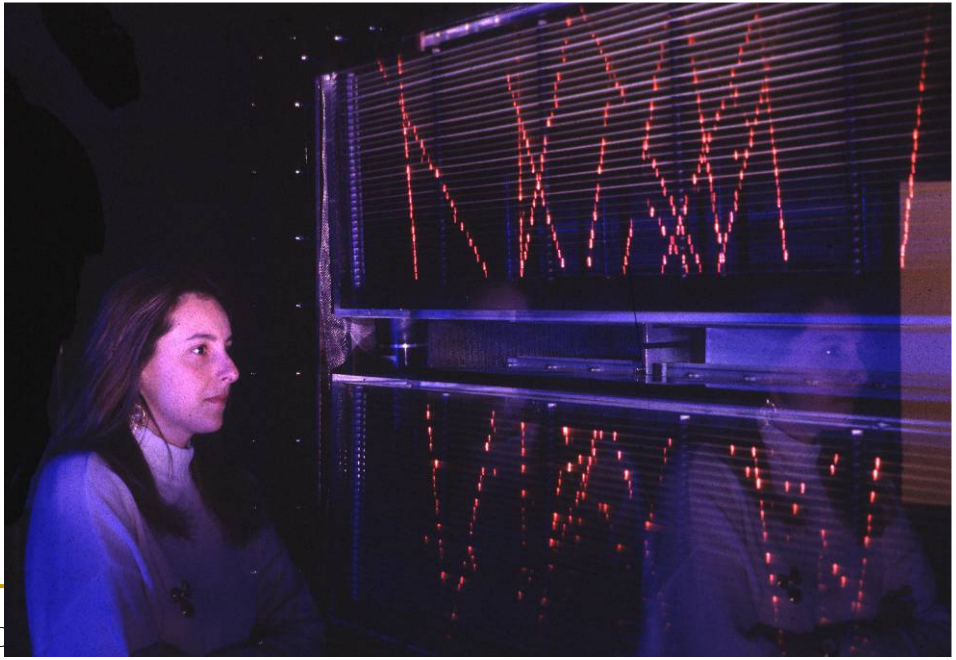
Full charge collection

Start of avalanche region

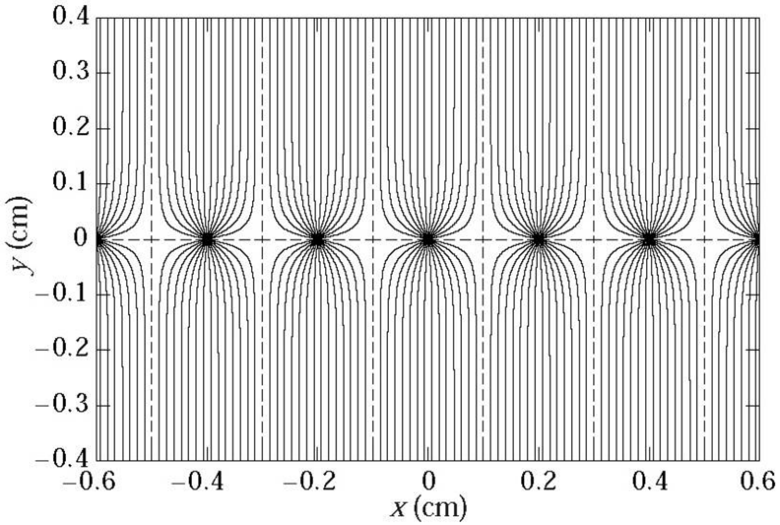
Geiger Region

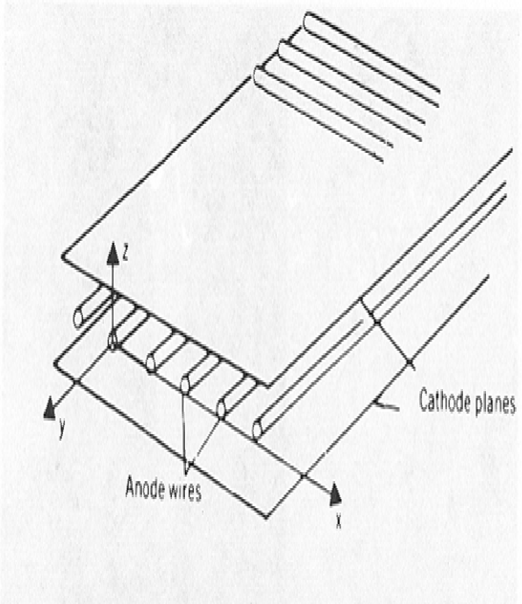
- Geiger Counter
- Spark Chamber
  - short bias pulse->localise breakdown
- Streamer Chamber
  - Large volume, transparent electrodes





MWPC

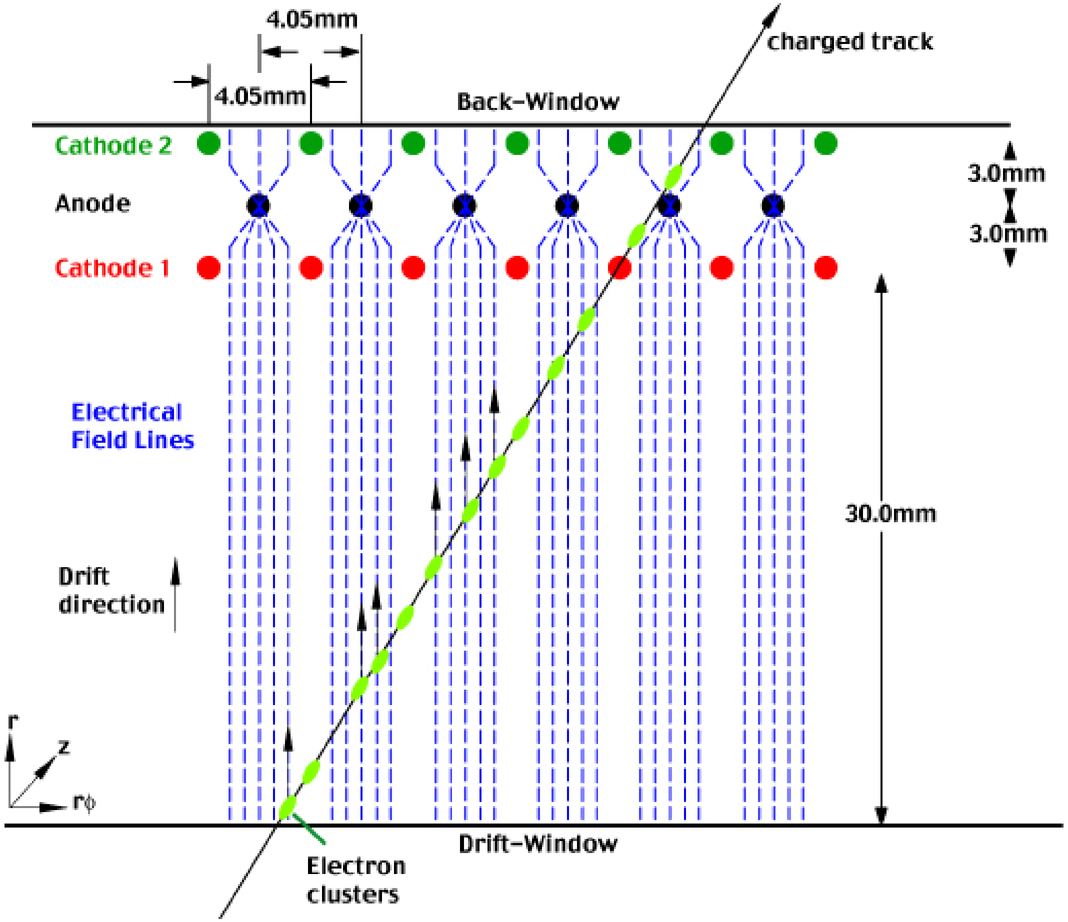




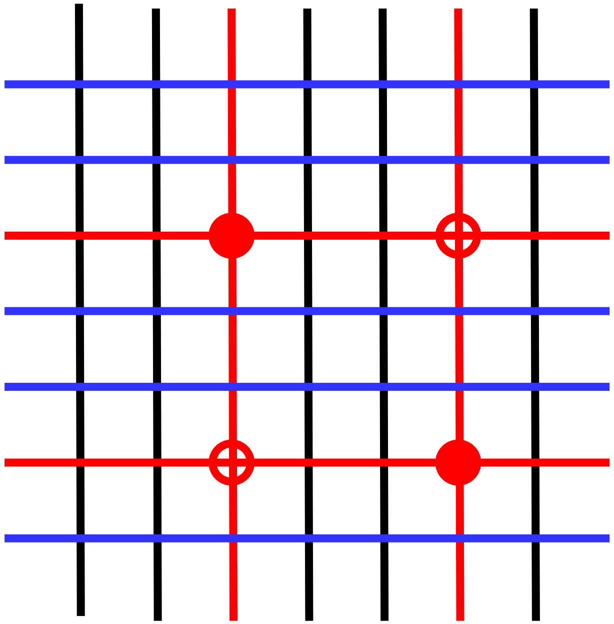
- Need better idea for large volume coverage at high rates
  - Multi-Wire Proportional Chamber
  - Fast
    - Ion Drift Velocity ~ 50 km/s (50 μm/ns)
  - Resolution ~pitch/√12
  - *x* from anode
  - *y* from ions at segmented cathode plane

Drift Chambers

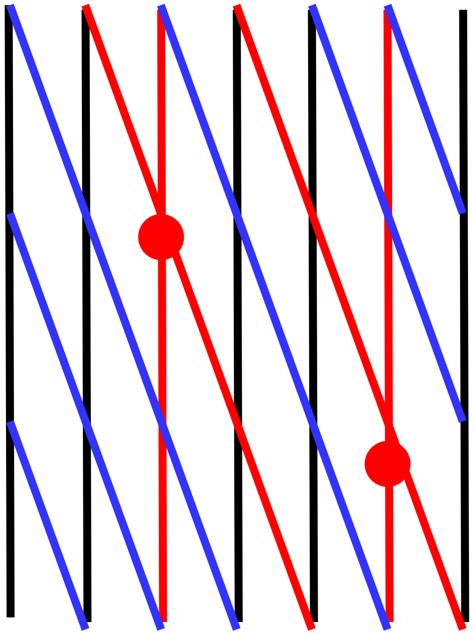
- Electron drift speed depends on electric field and gas
- Time delay of hit gives distance from sense anode
- Extra wires can be used to separate drift and avalanche regions
- Typical values:
  - drift distance ~cm
  - drift velocity ~ 50 km/s (50 µm/ns)
  - drift time ~µs
  - precision ~100 µm



Stereo Readout



- Good *z* resolution
- Need readout along length
- Ghost hits

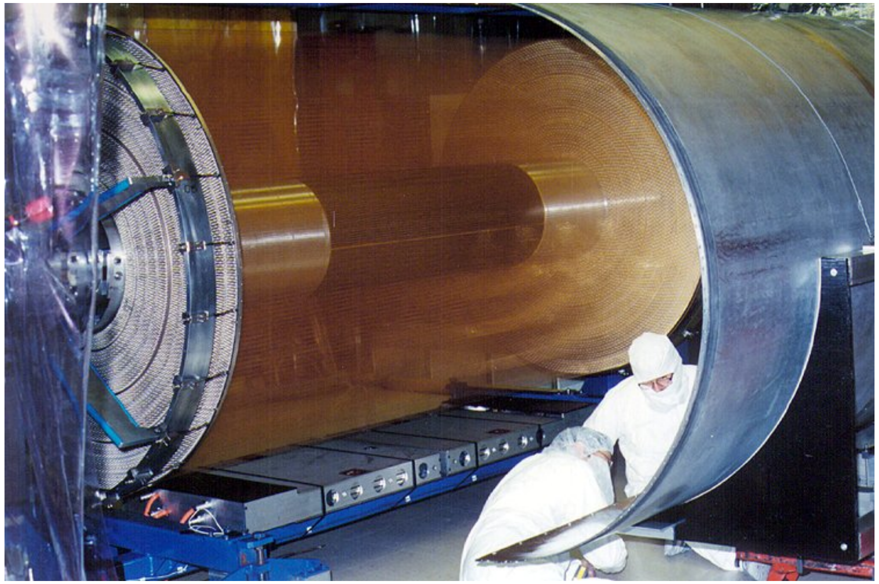


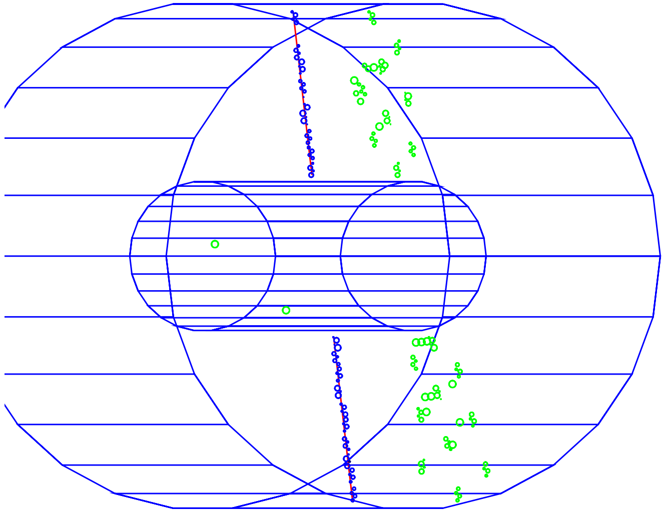
- Good pattern recognition
- Readout from ends
- Poor *z* resolution

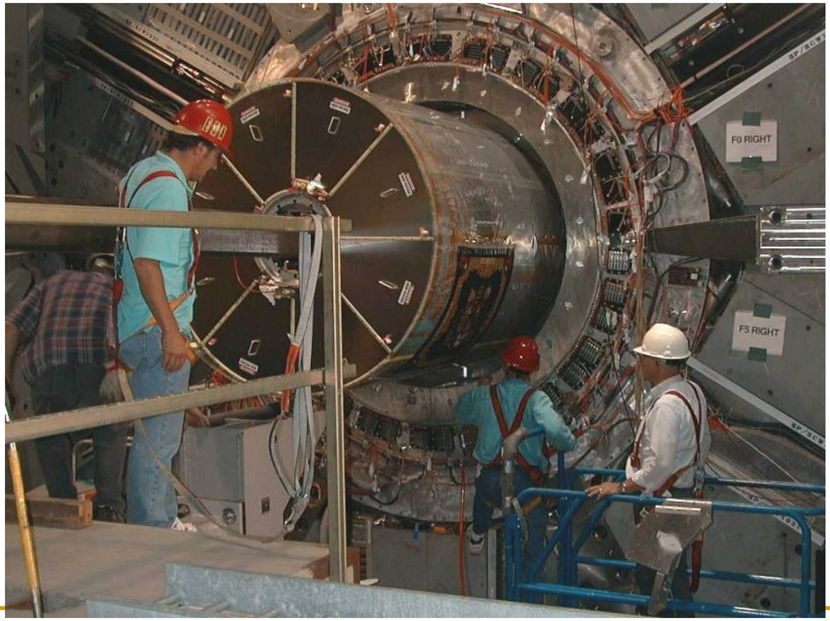
BaBar Drift Chamber

Open Cell Drift Chamber

- 2.8 m long
- Gas volume ~ 5.6 m^3
- 7100 anode wires
- Axial and stereo
- ~50,000 wires in total



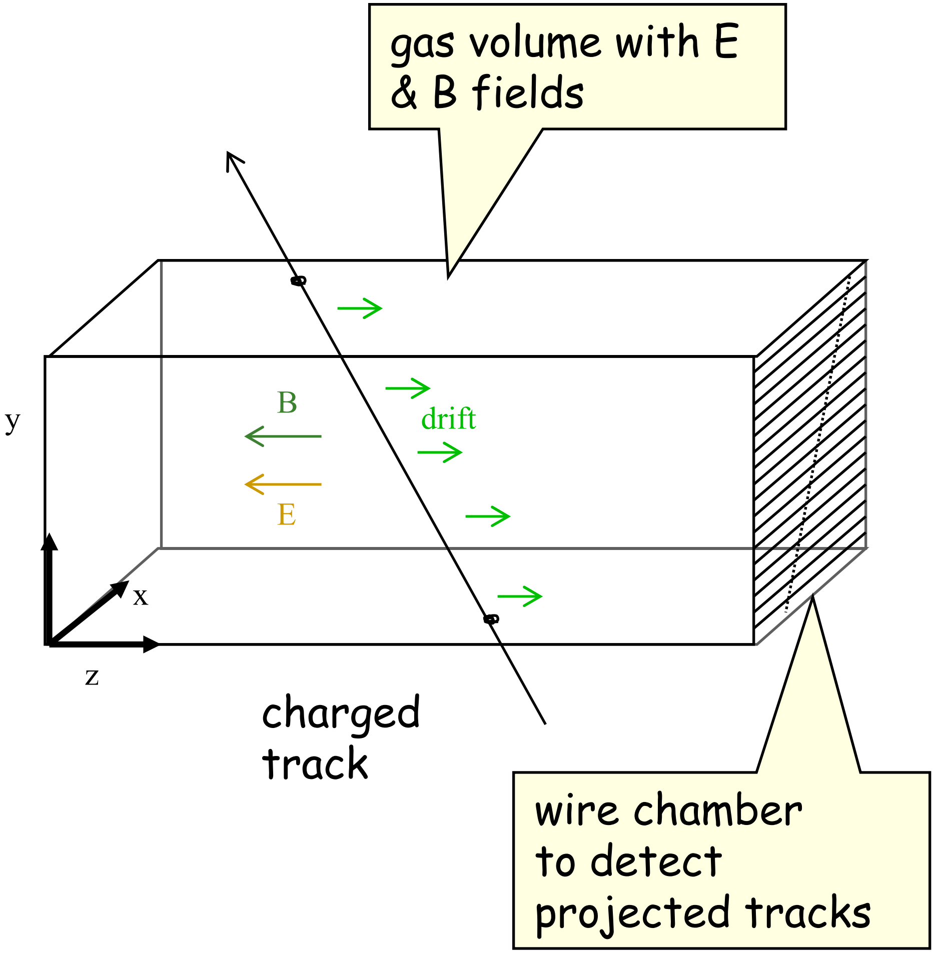




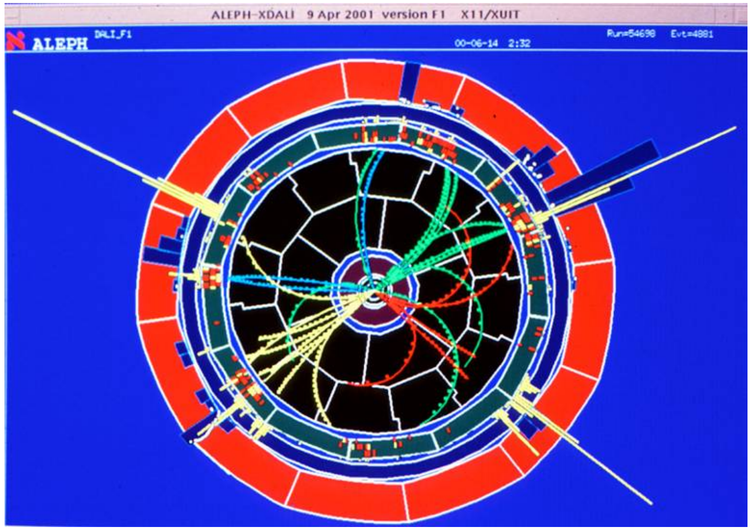
Time Projection Chamber

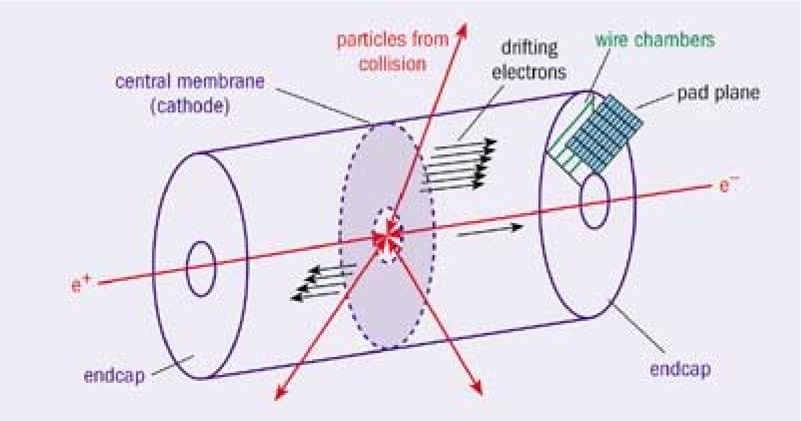
Ingredients:

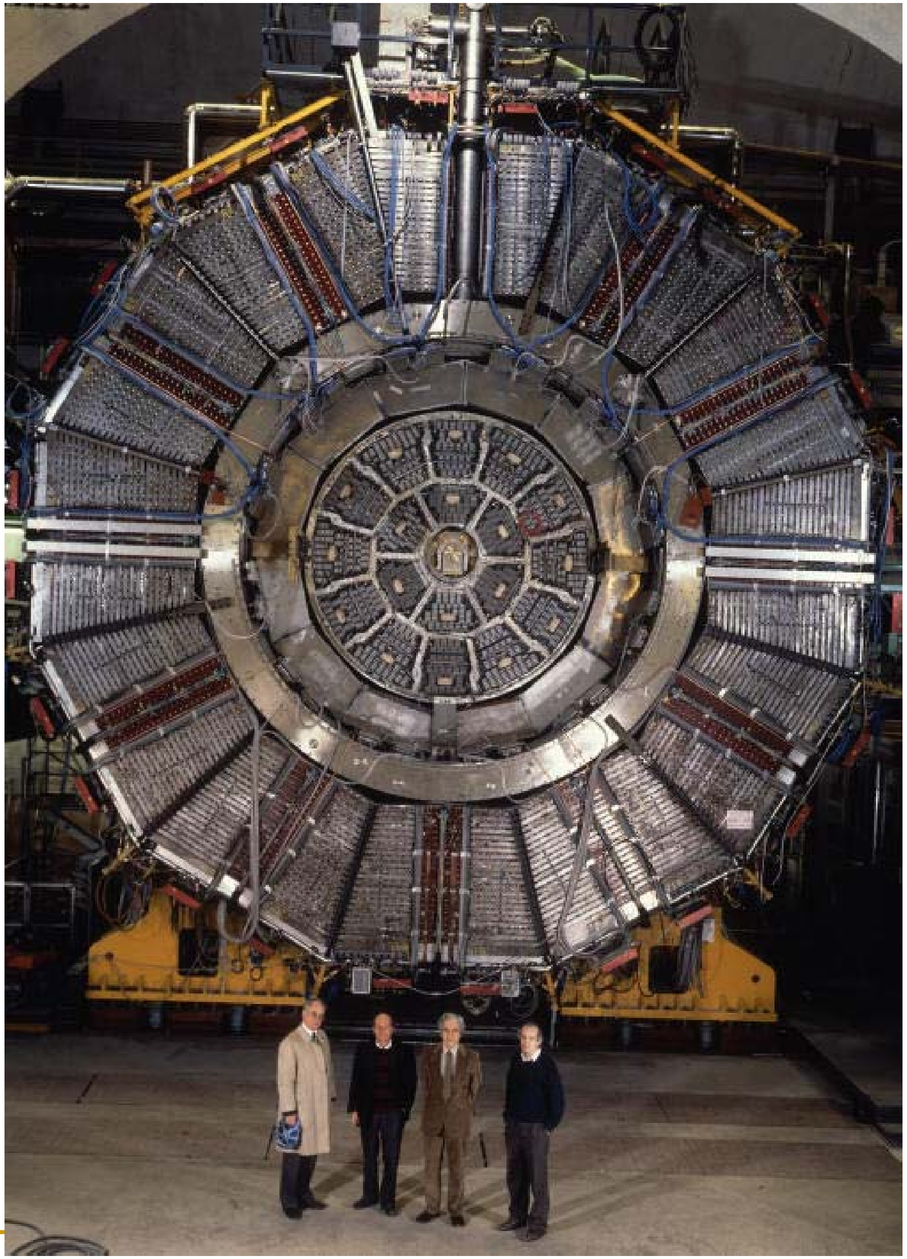
- Gas
  - E.g.: Ar + 10 to 20 % CH_4
- E-field
  - E ~ 100 to 200 V/cm
- B-field
  - as big as possible to measure momentum
  - to limit electron diffusion
- Wire chamber
  - to detect projected tracks
  - Timing gives z measurement
- Long drift distances
  - ~ metres



Detector with TPC



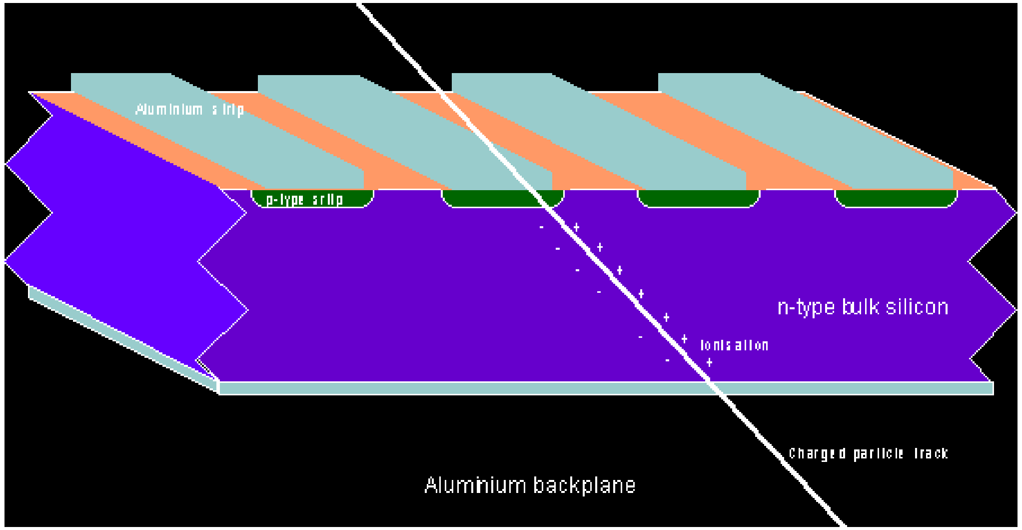




General considerations for Wire Chambers

- Gas, voltage and geometry must be chosen carefully.
  - precision, amplification, avalanche characteristics...
  - Chambers can be damaged.
- External magnetic field influences behaviour.
  - Must be measured and understood.
- MWPC:
  - fast, reliable
  - often used for triggering
- Drift/TPC:
  - large volume, reasonably precise
  - high incident fluxes can cause “short circuit”
  - long readout time
- Need other solution for high rates and/or extreme precision

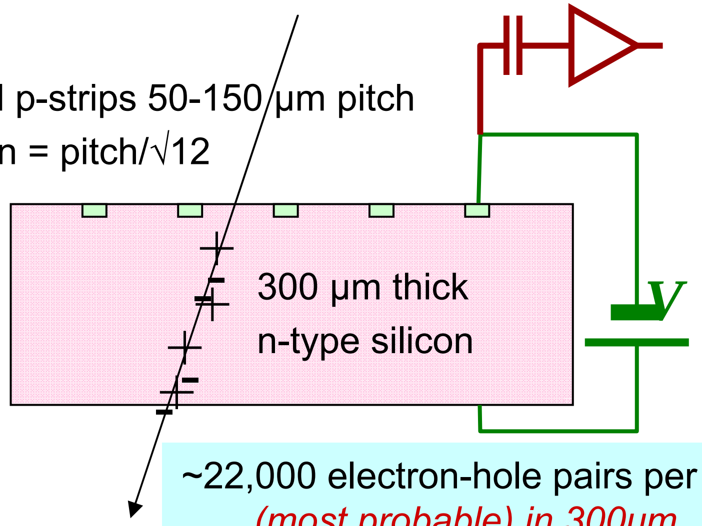
Silicon Strip Detector



- Particle physics needs detectors which can determine the position of particles with an accuracy of 0.01 mm, have minimal thickness (0.3mm), and have very fast (0.000000025 second) time response.
- Silicon, a semiconductor, can be fabricated in two forms; n type, with a surplus of electron sites in the crystal lattice, and p type, with a deficit of electron sites in the crystal lattice.
- The majority of silicon detectors consist of n type bulk material. The back face has an aluminium contact over the complete surface. The front face has p type silicon strips implanted in the surface. These p type strips aluminium strips on their surface. The aluminium strips are separated from their associated p type silicon strips by a thin insulator. An electric field is applied between the p strips and the back face.
- When a charged particle passes through a silicon detector it creates ionisation in the bulk of the silicon. This frees electrons from the atoms of the silicon and leaving these atoms with an electron vacancy. These vacancies are referred to as "holes".
- The "holes" "drift" in the electric field towards the negatively charged p type strips. The electrons "drift" towards the positively charged back plane.
- When the "holes" reach the p type strip they are collected and induce a measurable charge on the associated aluminium strip. The aluminium strips are connected to sensitive electronic read out channels.
- By recording which electronic channel fired, it is possible to determine where the charged particle passed through the detector.

Solid State Detectors

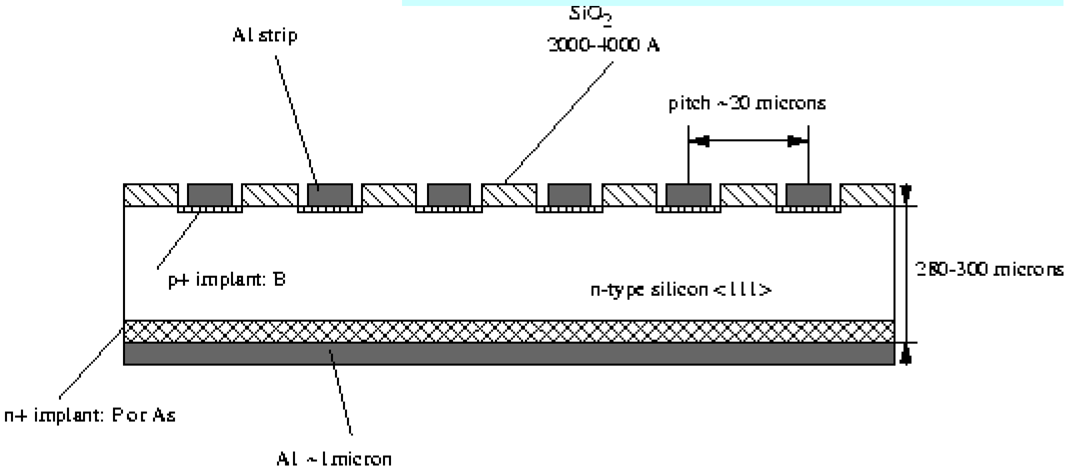
- Detect ionisation charges in solids
  - high density → large *dE/dx* signal
  - mechanically simple
  - can be very precise
- Semiconductors
  - small energy to create electron-hole pairs
  - silicon extremely widely used
    - *band gap 1.1 eV*
    - *massive expertise and capability in electronics industry*
- Resistors
  - plastic – cheap
  - diamond – robust, rad. hard
  - Germanium – can be made thick



Implanted p-strips 50-150 μm pitch

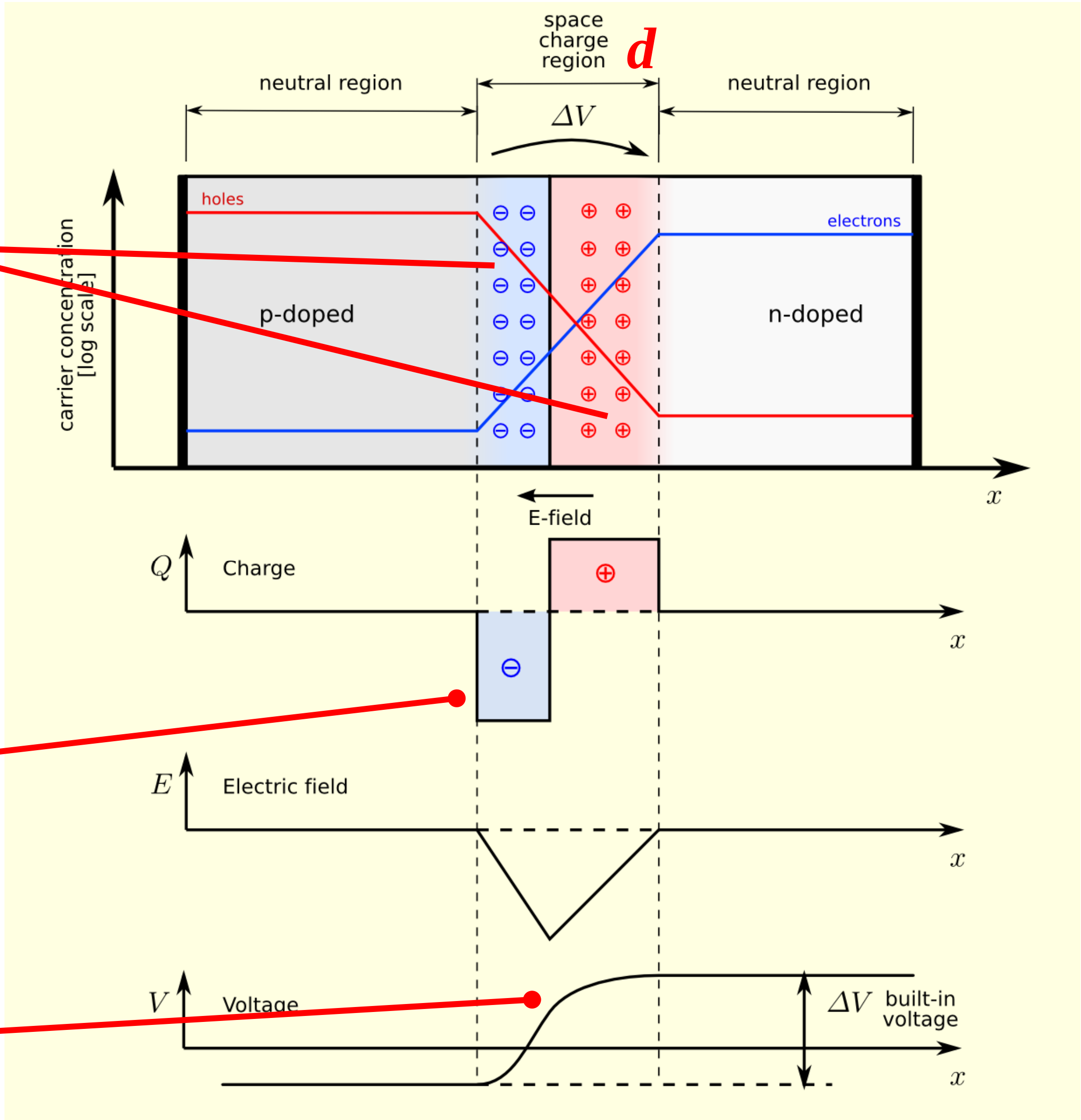
Resolution = pitch/√12

~22,000 electron-hole pairs per MIP *(most probable) in 300μm*



Reminder: p-n Junctions

http://britneyspears.ac/physics/pn/pnjunct.htm



Silicon doped to change electrical properties

Charge carriers diffuse out of depletion region

Net space charge ⇒ electric field

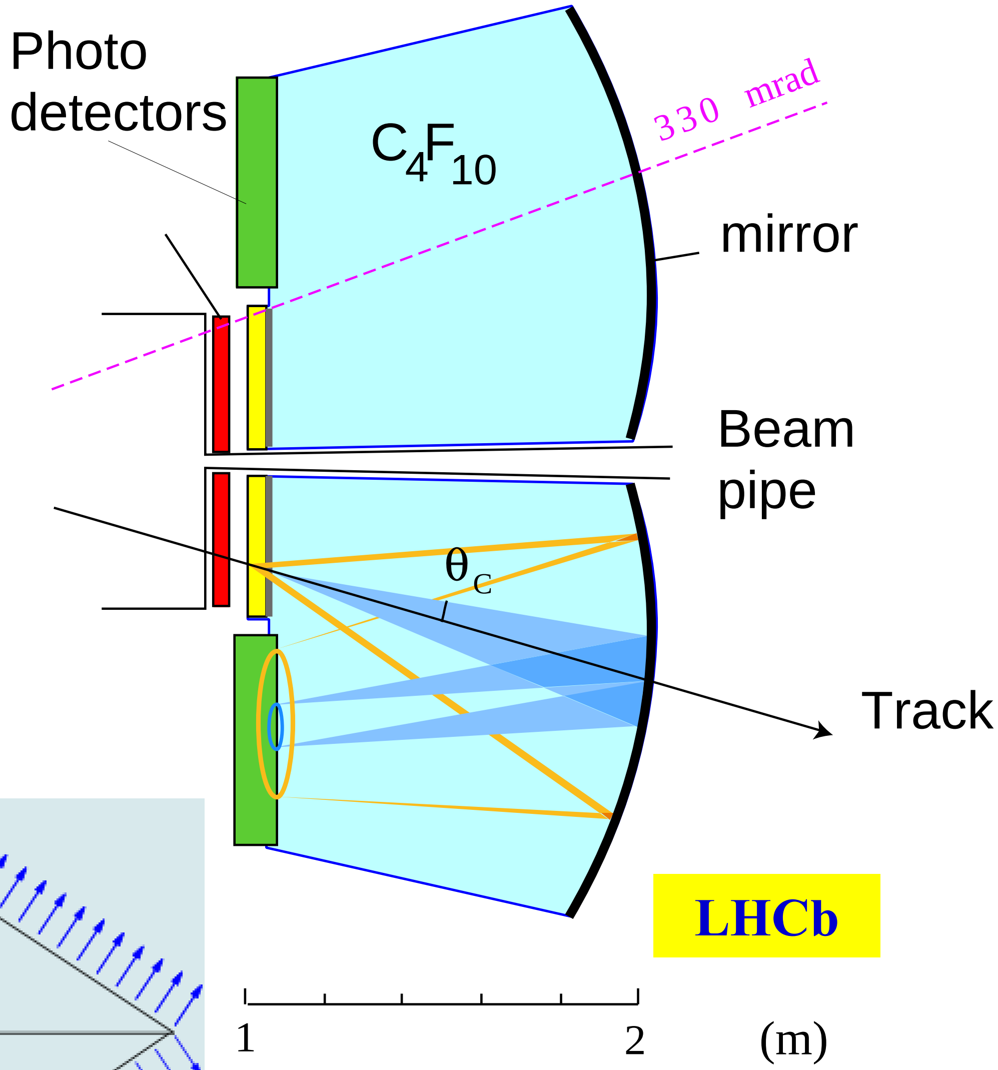
Intrinsic depletion can be
increased by reverse
bias

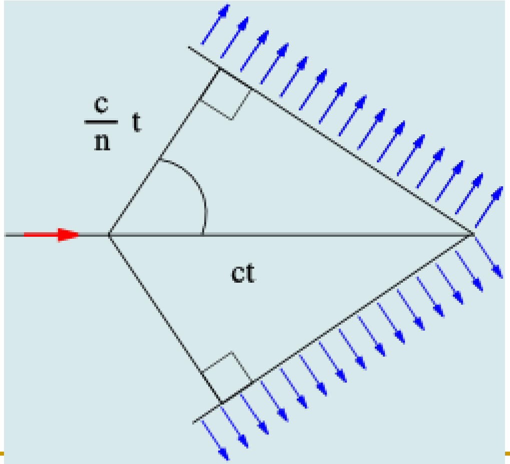
Space Charge Region, d

$$d \approx 0.5\left[\mu\text{m}/\sqrt{\Omega\text{cm.V}}\right]\sqrt{\rho(V+0.5)}\ \mu\text{m}$$

Cerenkov Detector

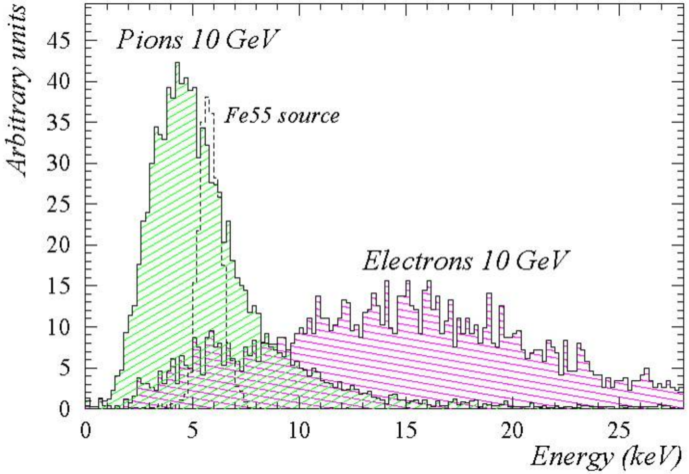
- Cerenkov Radiation
  - A charged particle will radiate energy if its velocity is greater than the local phase velocity of light
  - speed of light in medium = c/n
  - n = refractive index
  - charged particles produce light “shock waves” if v>c/n
  - light cone cosθ = c/vn = 1/(nβ)
  - “eerie blue glow”
  - Useful for separating pions and kaons





Transition Radiation Detector

GLAST launches May 16
http://www.nasa.gov/glast



GLAST

- An energetic charged particle moving through matter momentarily polarizes the material nearby. If the particle crosses a boundary where the index of refraction changes, the change in polarization gives rise to the emission of electromagnetic transition radiation.
- About one photon is emitted for every 100 boundaries crossed. Transition radiation is emitted even if the velocity of the particle is less than the light velocity of a given wavelength, in contrast to Cerenkov radiation. Consequently, this radiation can take place in the x-ray region of the spectrum where there is no Cerenkov radiation, because the index of refraction is less than one.
- At each interface between materials, the probability of transition radiation increases with the relativistic gamma factor. Thus particles with large γ give off many photons, and small γ give off few. For a given energy, this allows a discrimination between a lighter particle (which has a high γ and therefore radiates) and a heavier particle (which has a low γ and radiates much less).
- Useful for separating pions and electrons

Next Time...

More interactions and detectors