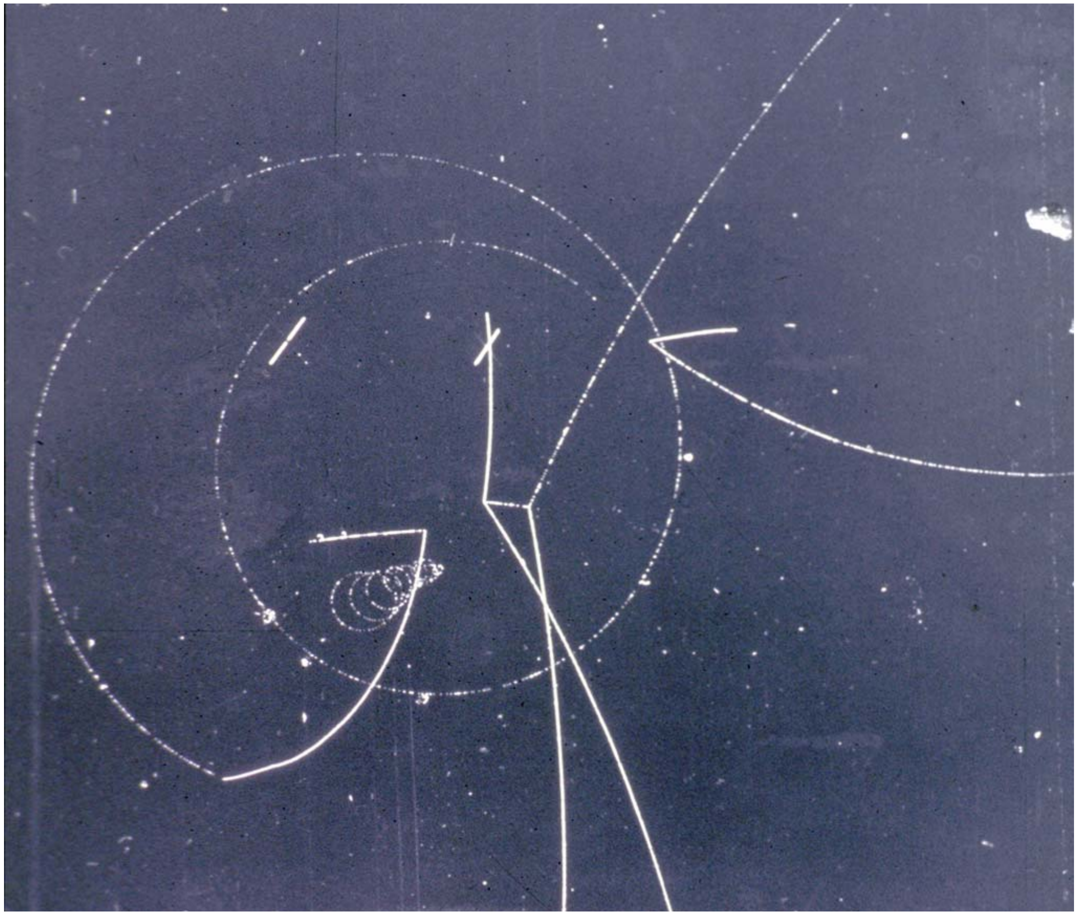
# Next Part of Course: How detectors work



... starting with tracking of charged particles

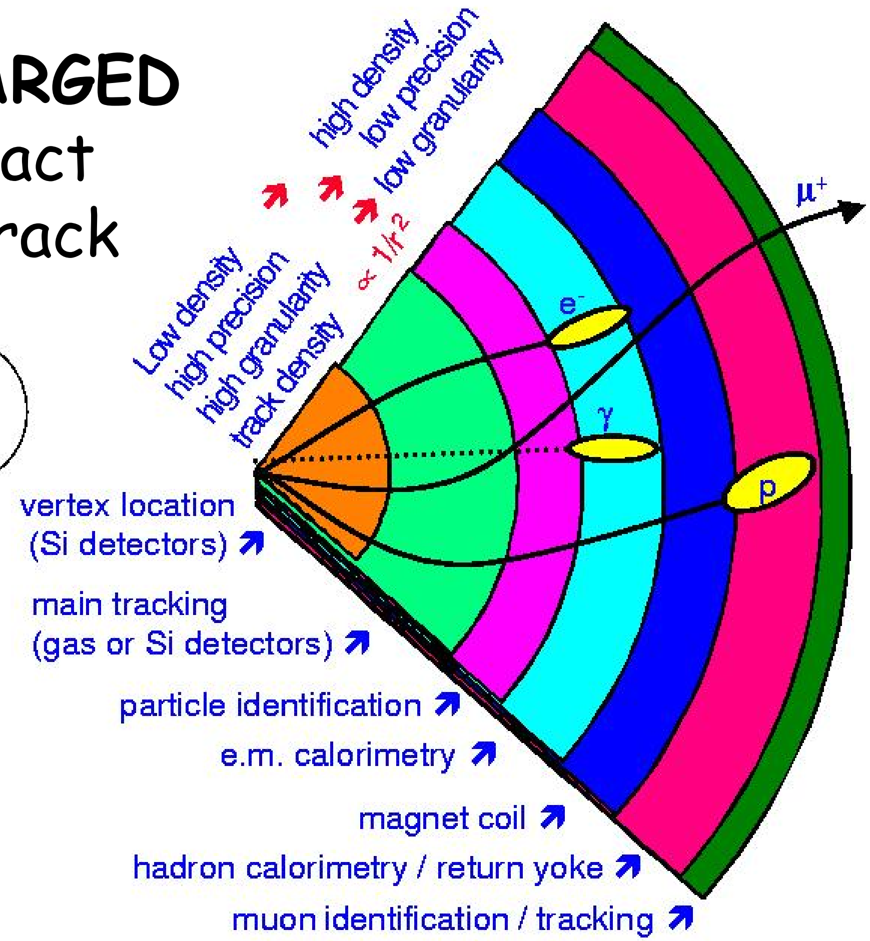
... an old subject with applications way beyond particle physics!

**Today: Gaseous tracking detectors**

Annihilation of an antiproton in the 80 cm Saclay liquid hydrogen bubble chamber. A negative kaon ($K^-$ meson) and a neutral kaon ($K^0$ meson) are produced in this process as well as a positive pion ($\pi^+$ meson).

# Tracking Detectors in Context

- To detect a particle, we have to make it interact with our detector!
- Tracking detectors detect **CHARGED PARTICLES** … want them to interact as little as possible to precisely track the particle trajectory in conditions as close to vacuum as possible.
- In calorimeters, we want them to interact as much as possible to stop the particle and measure all of the energy it leaves behind.
- Trackers are therefore located inside calorimeters!
- Also often provide an important role in triggering events



# Interaction of Charged Particles with Matter

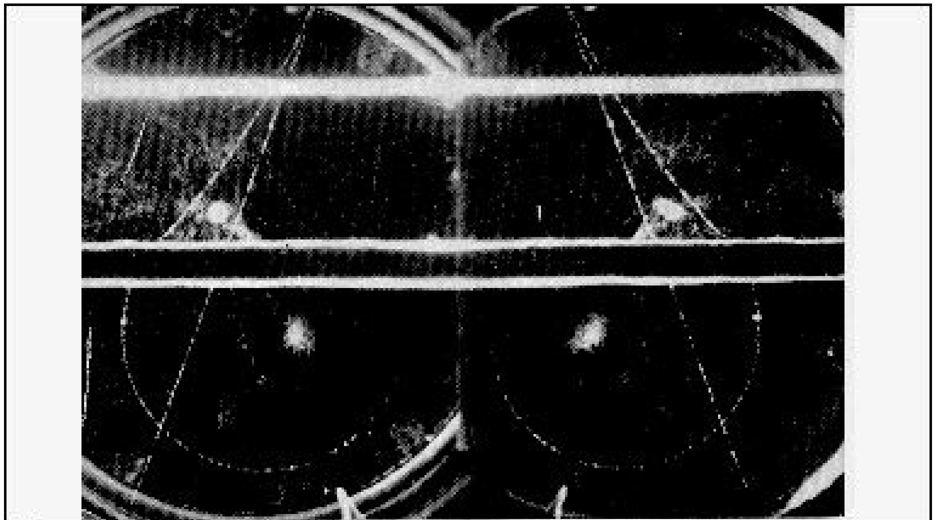
- Multiple Coulomb (electromagnetic) Scattering
- Ionisation
- Bremsstrahlung (especially electrons) – see calo lecture
- Nuclear Interactions (hadrons) – see calo lecture

- Charged particle detectors rely on **IONISATION**.
- Measurement accuracy usually limited by Multiple Coulomb Scattering
- The measured quantity is the **MOMENTUM** (see next time)

Tracking detectors should ....

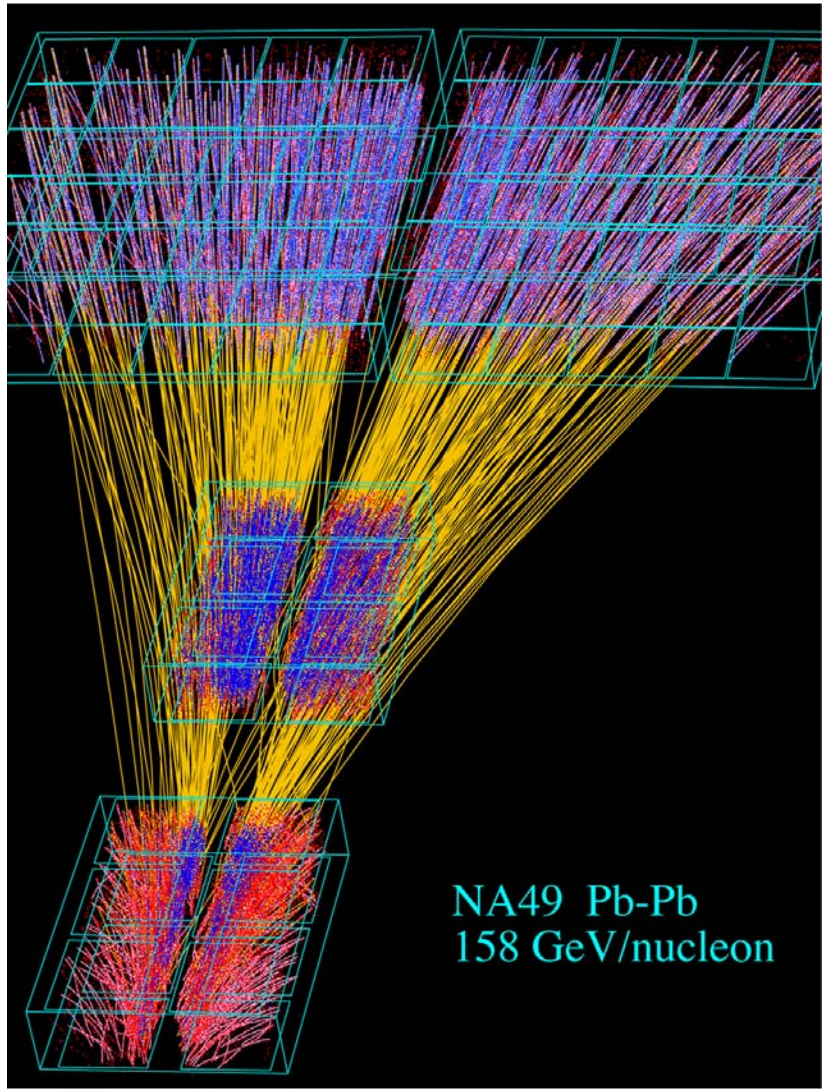
- be made from low density material
- have minimal dead material between them and the interaction

# A Hundred years of Particle Tracking




**1900:Cloud Chamber**
Supersaturated vapour condenses to tiny liquid droplets around ions

Different centuries, same principle!... persuade the particle to ionise and collect the resulting charge




**2000:Time Projection Chamber**:
>1000 tracks!

# Energy Loss by Ionisation in Gas

- Primary energy loss by ionisation of atoms leads to creation of ion-electron pairs a gas volume.
- Number of **primary ionisation pairs is small**
- Primary ionisation depends on particle type and medium
- **Bethe Bloch formula** describes this over much of the interesting kinematic range (basically from Rutherford scattering, with some quantum and relativistic corrections (see eg Fernow, Perkins or Particle Data book).

$$\frac{dE}{dx} \sim C.\left(\frac{z}{\beta}\right)^2.\ln\gamma$$

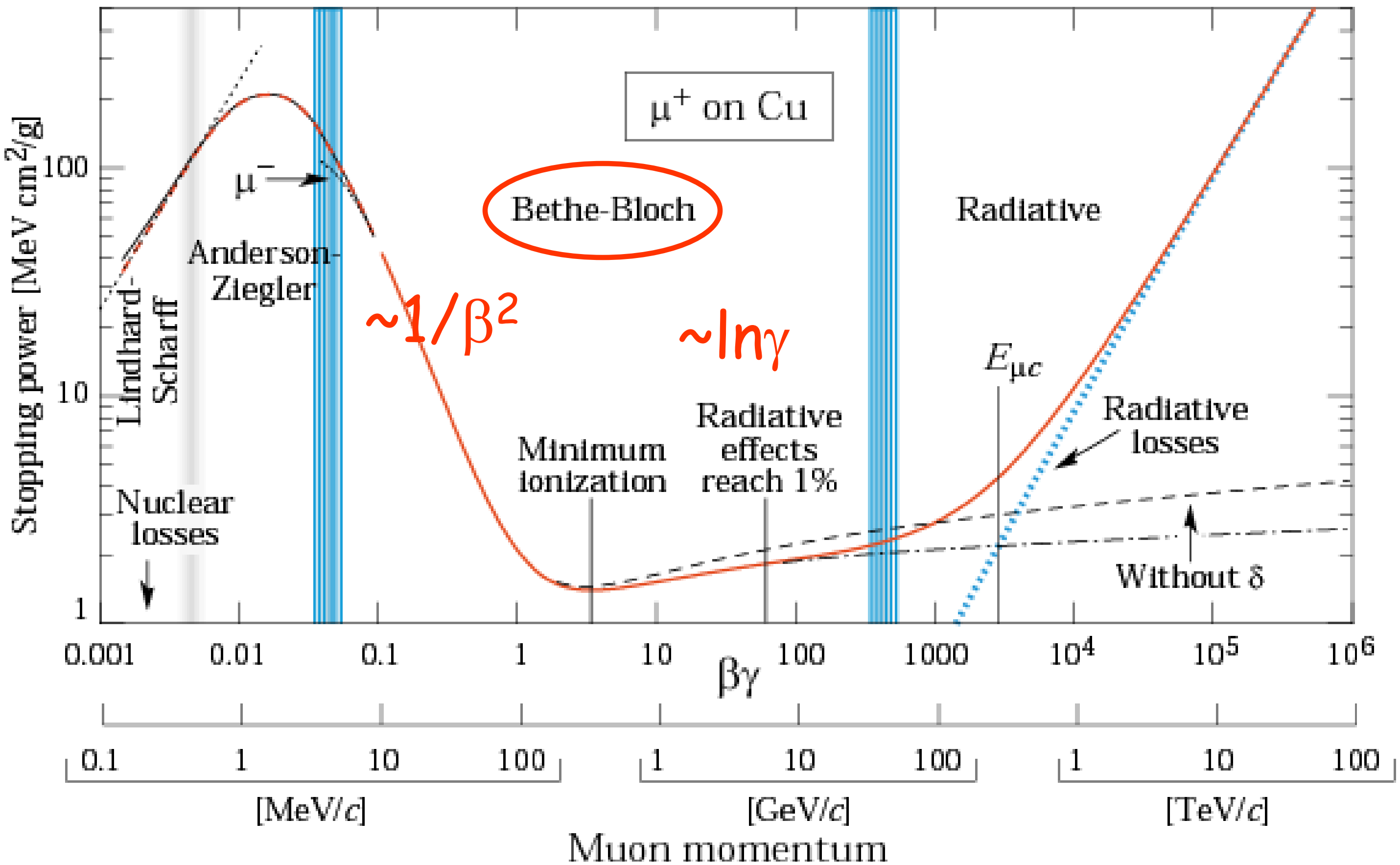
($\beta=v/c$, $\gamma=1/\mathrm{sqrt}(1-\beta^2)$)

- Depends quadratically on charge and velocity of particle, but not its mass. →Particles with same momentum but different mass can be distinguished!
- Constant *C* depends on gas

$\sim 1/\beta^2$ at low momentum, $\sim \ln\gamma$ at high mom, minimum in between

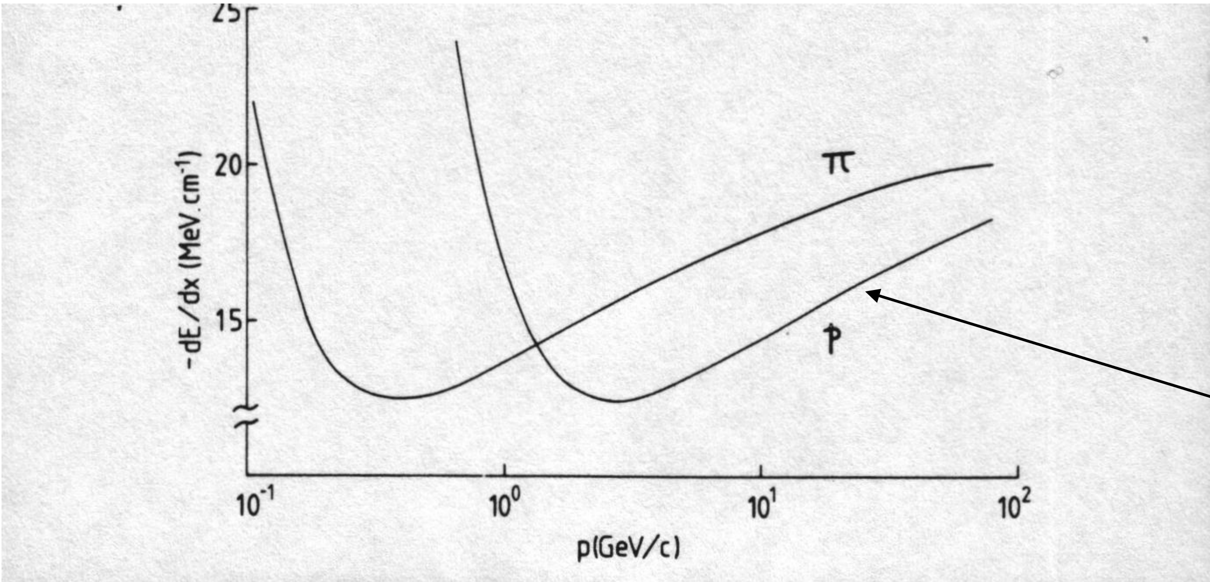
# Example … dE/dx for a Muon

$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$




Muons often said to be minimum ionising particles, since their dE/dx lies in the minimum region over huge momentum range

# Particle Identification with dE/dx

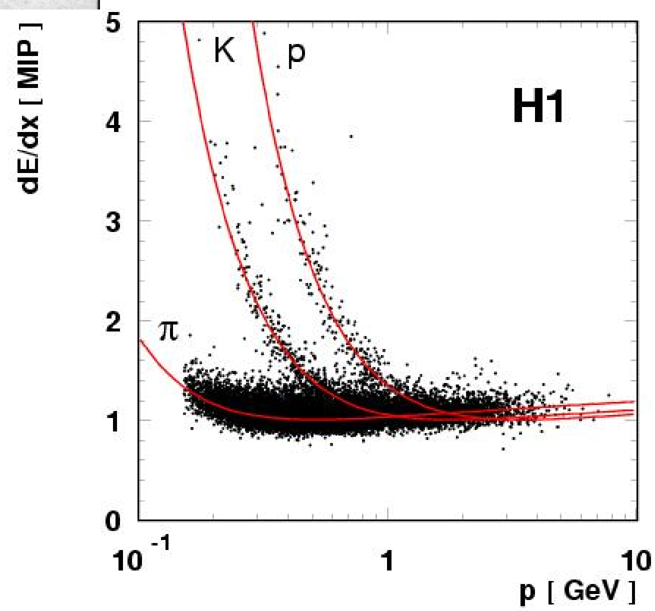



Ionisation deposit per unit distance

$$\frac{dE}{dx} \sim C.\left(\frac{z}{\beta}\right)^2 .\ln\gamma$$

**Relativistic rise**

**~log γ**

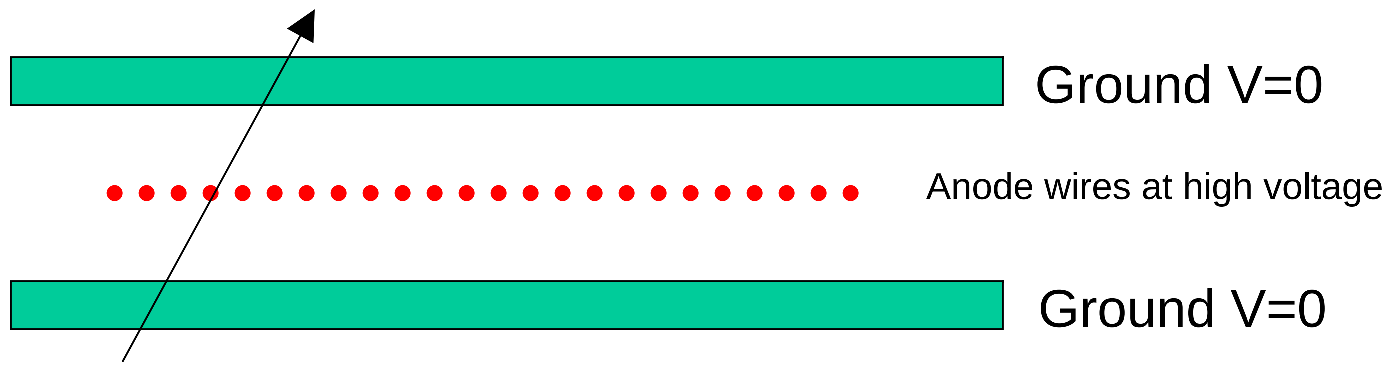



Example from H1 experiment … dE/dx used to distinguish kaons, pions, protons at low momentum

# Ionisation Signal Collection with Electric Field

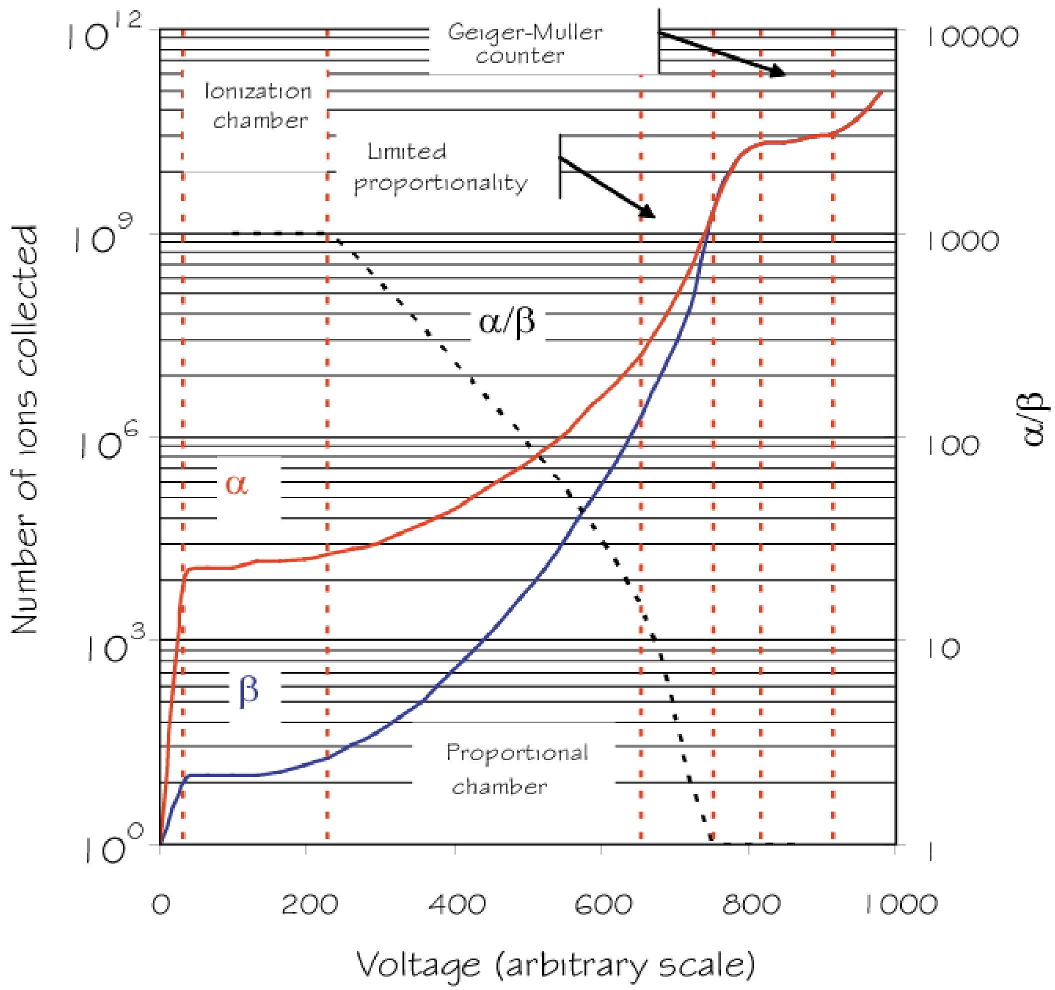
… most common modern method of collecting the ionisation … Ionisation chamber consists of gas to be ionised in `drift space', enclosed in uniform electric field.

Liberated electrons drift to anode wires




- Close to the anode the field is strong: the electrons are accelerated such that they produce secondary electrons, which make more electrons via Bremsstrahlung etc ......................an ***AVALANCHE*** resulting in a large ***GAIN***!
- Use dense inert gases (e.g. Argon) with various admixtures

# Gas Detector Operation Modes




Response curves for α (highly ionising) and β (~ minimum ionising) particles

- ❑Ionisation mode: No gas multiplication, signal from primary electrons only (used in dosimetry)
- ❑Proportional mode: Signal proportional to energy loss of particle (dE/dx). Gain of order 10^5 (used in most detectors).
- ❑Limited proportionality: Space charge effects of ions alter effective electric field.
- ❑Geiger Mode: Electric breakdown of gas. Recombination of ions result in photo-emission. Avalanches merge -> spark emission (damages detector!)

# Geiger Mode

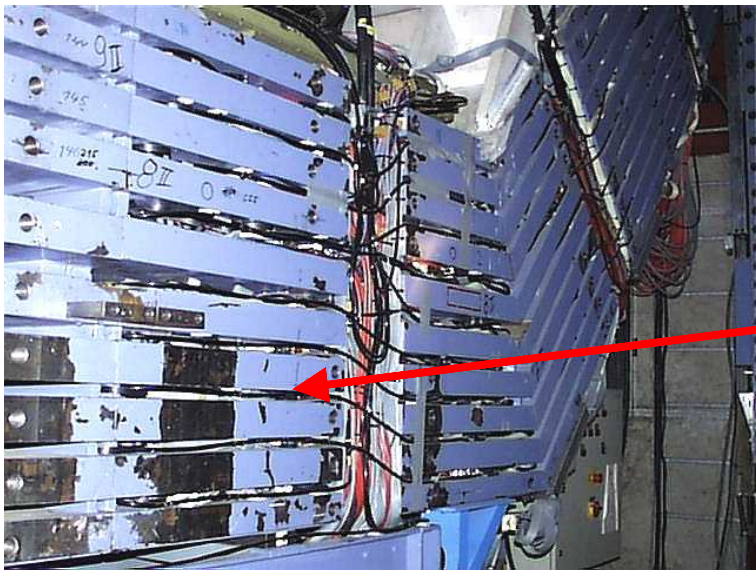
- Modern detectors don't use Geiger mode
- Sparks in sensitive detectors are damaging!

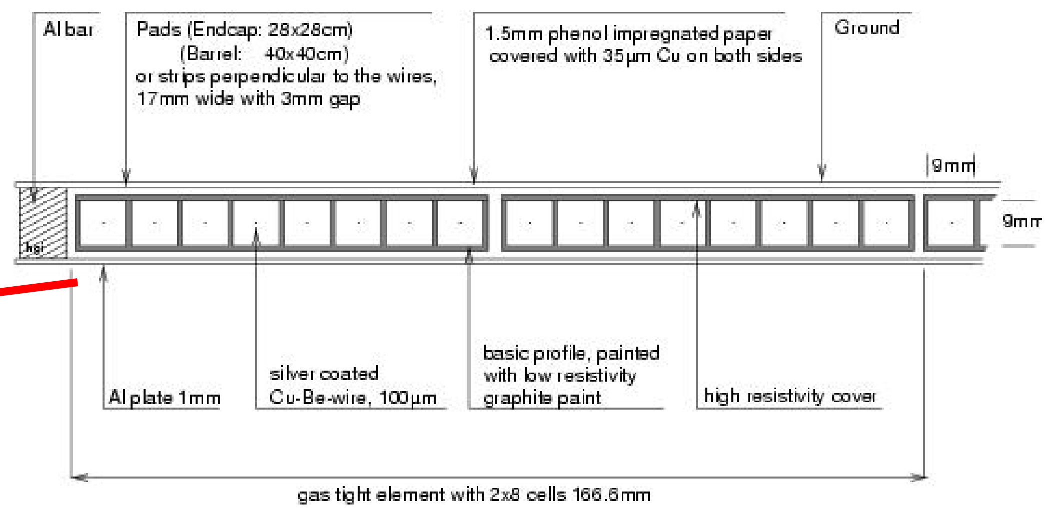

…. but Spark Chambers are a great way of visualising particles such as cosmic muons

See e.g. the Birmingham Spark Chamber project (Dr Wilson)

# Limited Streamer Tubes

- H1 muon detectors operate in limited proportionality mode
- Iron return yoke of magnet instrumented with gas chambers
- Thick wires, highly quenched gas

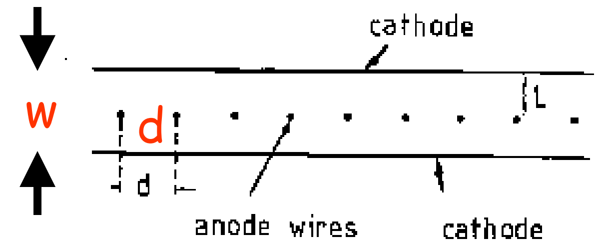




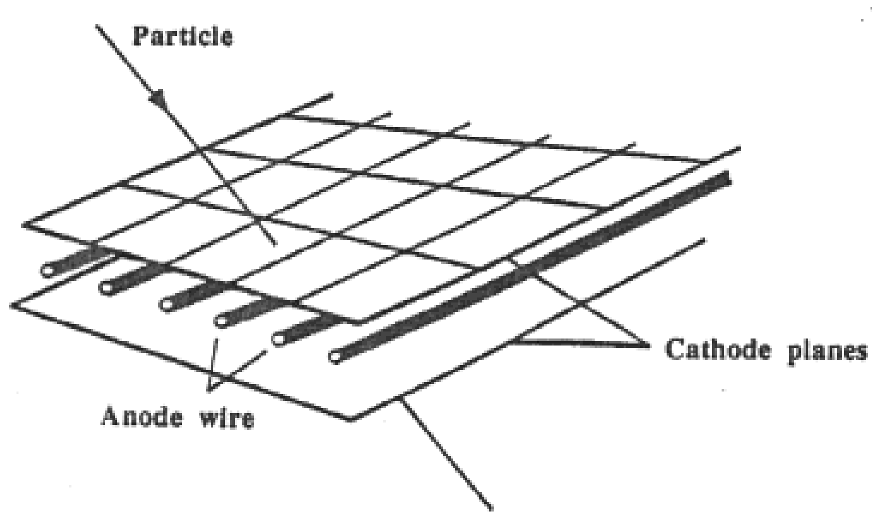

- Signal no longer proportional to primary ionisation
(→ no particle ID, but who cares, we know they are muons!)
- Easy to build, large & efficient signal, simple electronics

# Multi-Wire Proportional Chambers

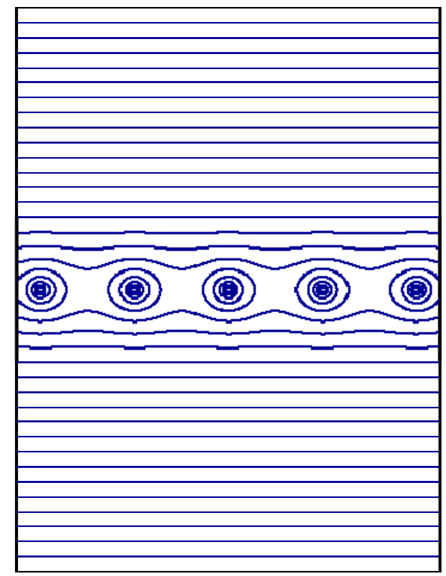
G. Charpak et al. 1968, Nobel Prize 1992




Typically d=2mm,w=8mm

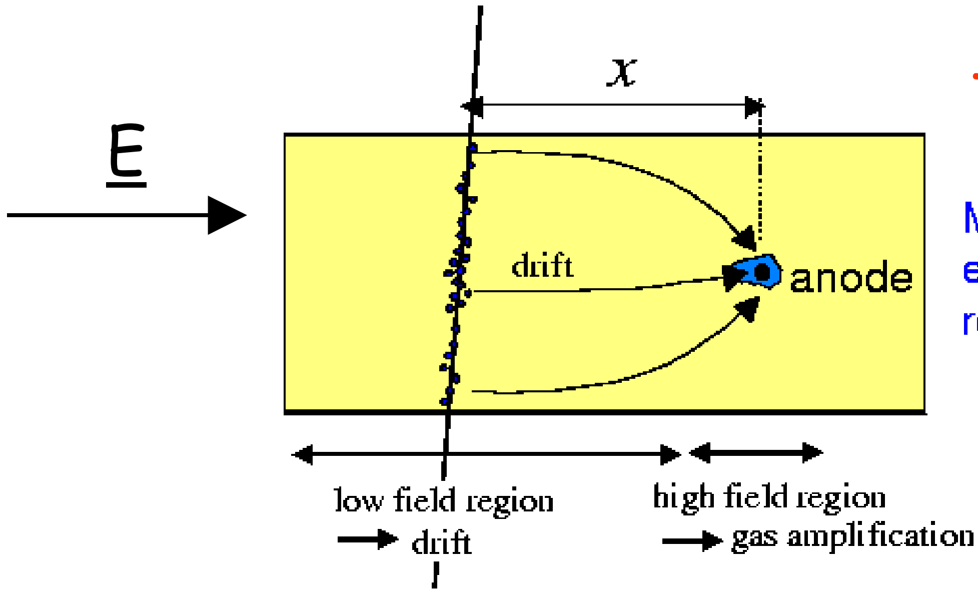



Field map:
Low field
between
anodes



- Large number of electrically isolated cells
- Proportional mode. – 1D info, multi-layers for precision and 3D signal
- Digital readout of anode pulses
- Fast response, **ideal for triggering**
- Poor spatial resolution ~500μm, determined by (but less than) cell size.

# Drift Chambers and Precision Tracking




Much wider wire spacing than MWPCs

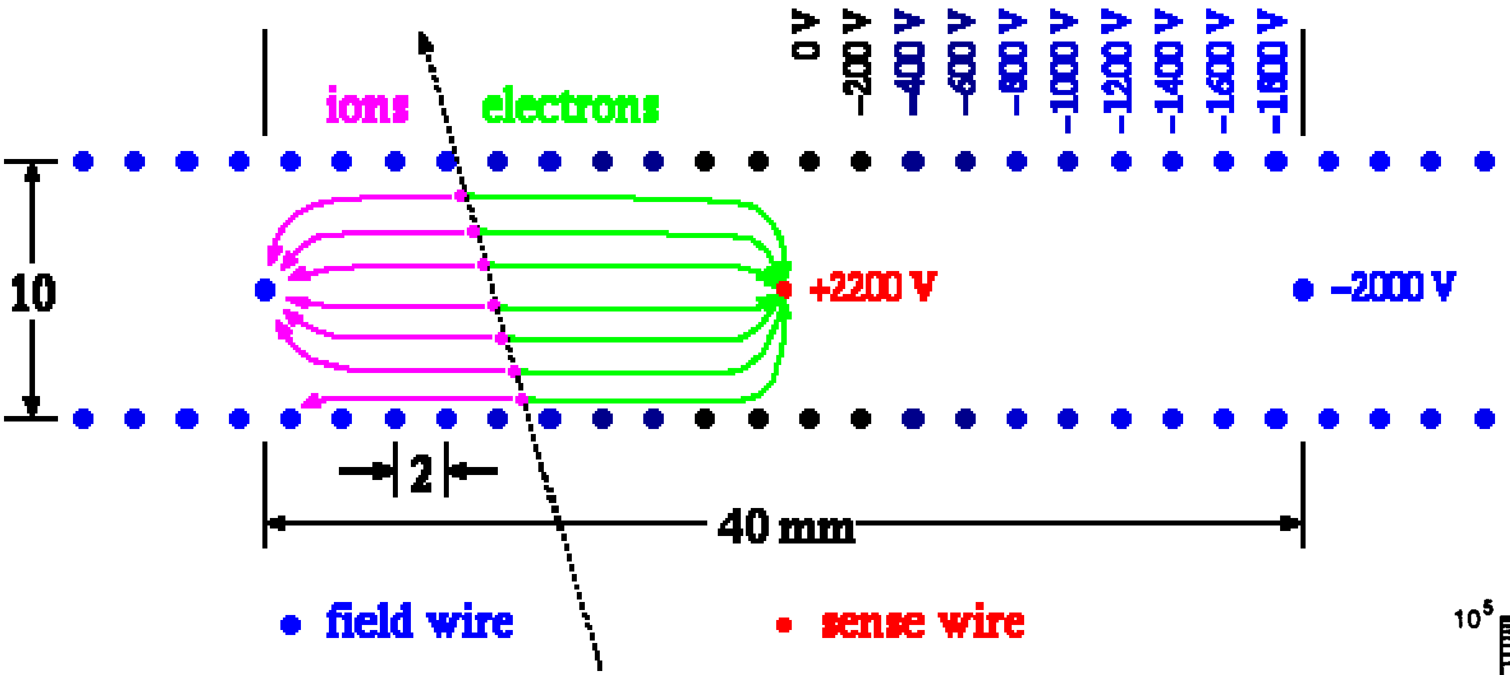
Measure arrival time of electrons at sense wire relative to a time $t_0$.

$$x = \int v_D(t)\,dt \sim v_D.\Delta t$$

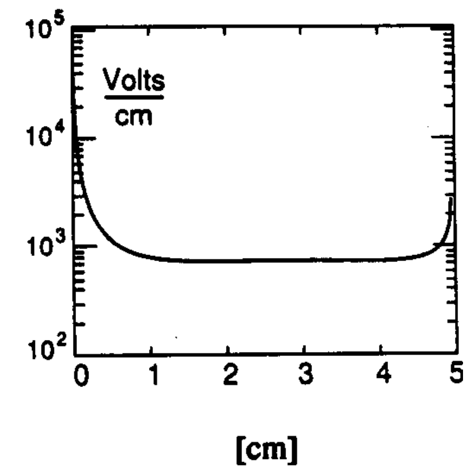
- Electrons drift towards anode with precisely known velocity, determined by gas mixture and field.
- Measuring signal arrival time gives precise spatial information if we also know the primary interaction time (i.e. which bunch crossing) from other detectors such as MWPCs.
- Very uniform field between anode wires required for constant drift velocity

# Field Shaping in Drift Chambers

- Uniformity of drift field achieved by adding lots of field shaping wires in addition to anode wires … it's complicated!
- Then electron drift velocity ~ constant, typically 5 cm / ms

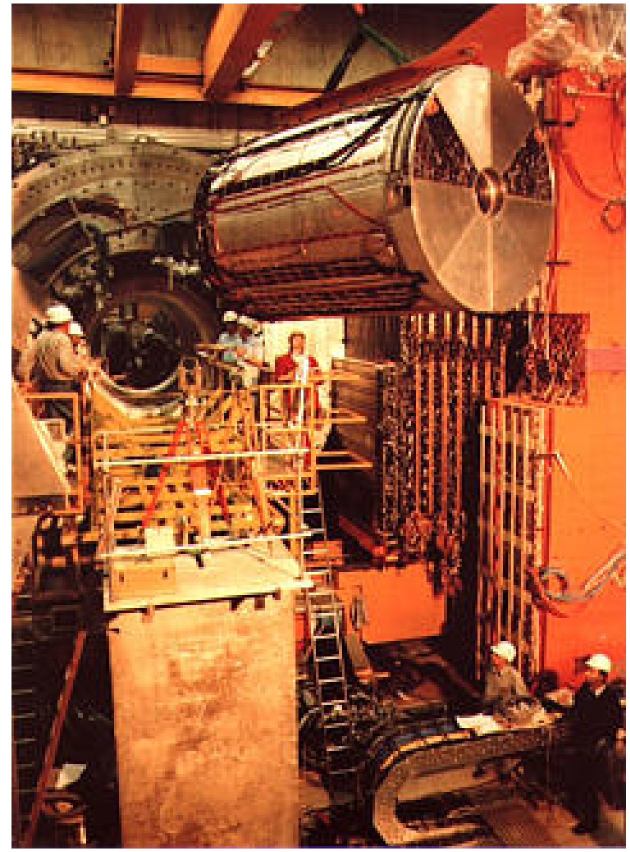


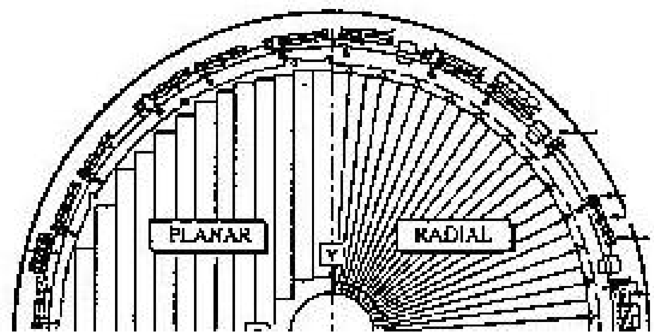

Overall field




… end result is one precise coordinate perpendicular to wires…

# Drift Chamber Examples



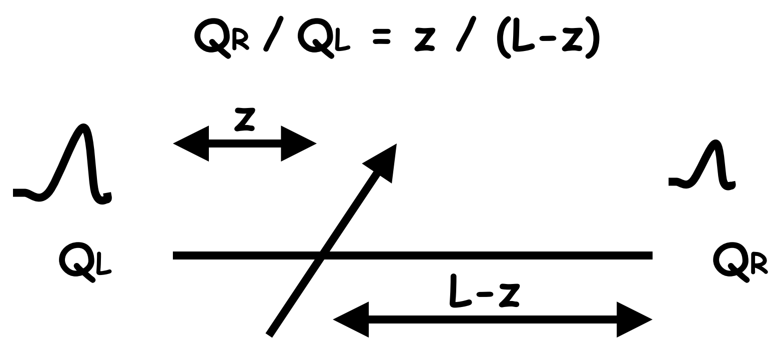

- Planar chambers give coordinates of track intersection with plane
- Radials give r/$\phi$ information
- Multiple layers with different wire orientations perpendicular to beam can give full 2D (transverse) trajectory information.
- Imagine the damage a single broken wire could do!

# Measurement of (z) Coordinate along Wire

Several methods available:

-z-chambers: just add more chambers with sense wires perpendicular to beam-pipe ($\sigma(z)$ ~ 200$\mu$m)

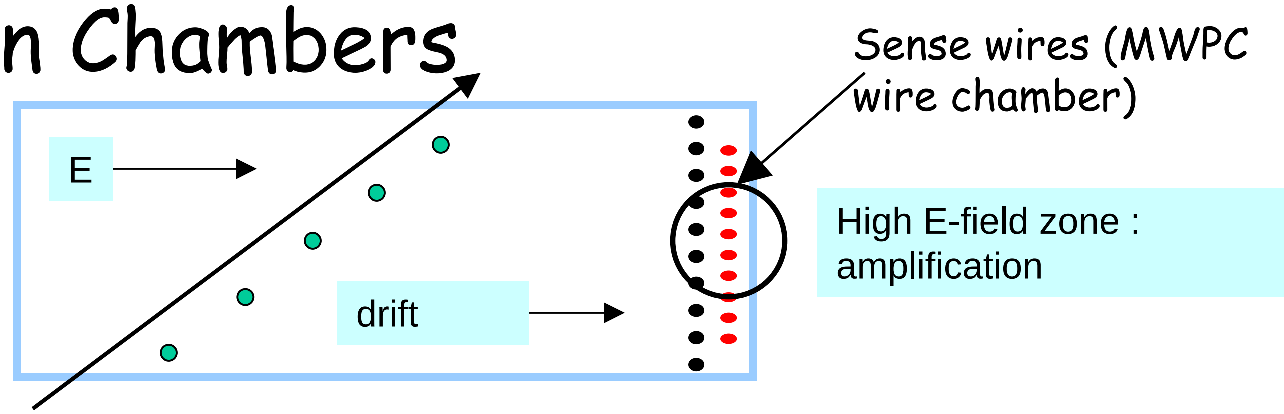
-Charge division: Read out charge at both ends of sense wire ($\sigma(z)$ ~1% of track length, ~2cm)



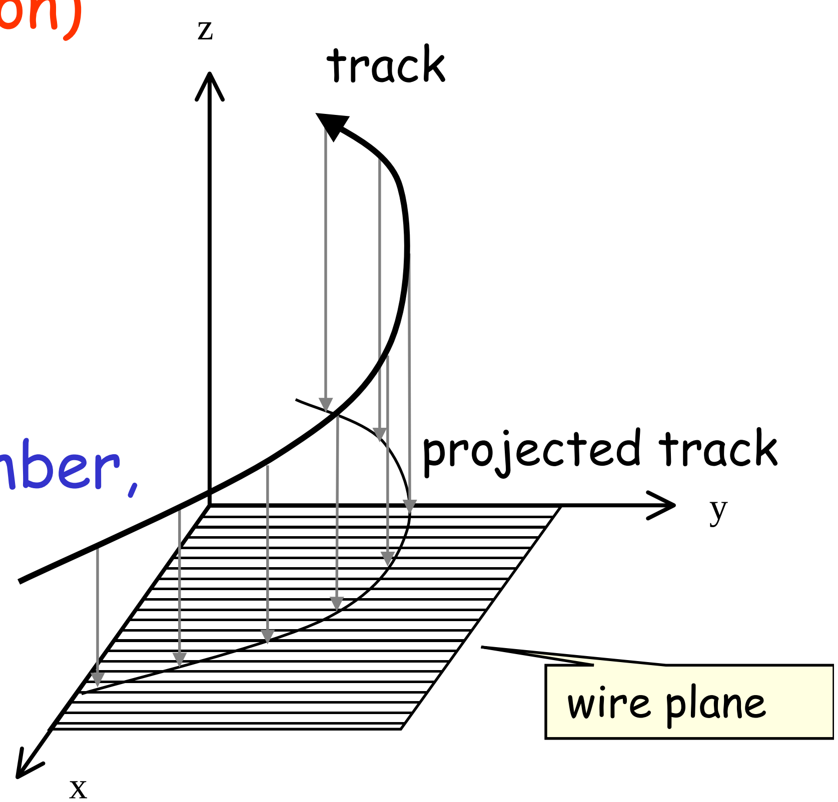

- z By Timing: Similar idea, with timing of signals instead of Q.

-Stereo chambers: rotate end points of one end of sense wire by small angle ... x-y measurement becomes a function of z -> can get information on z by comparing many wires ($\sigma(z)$ ~ 1mm)

# Time Projection Chambers

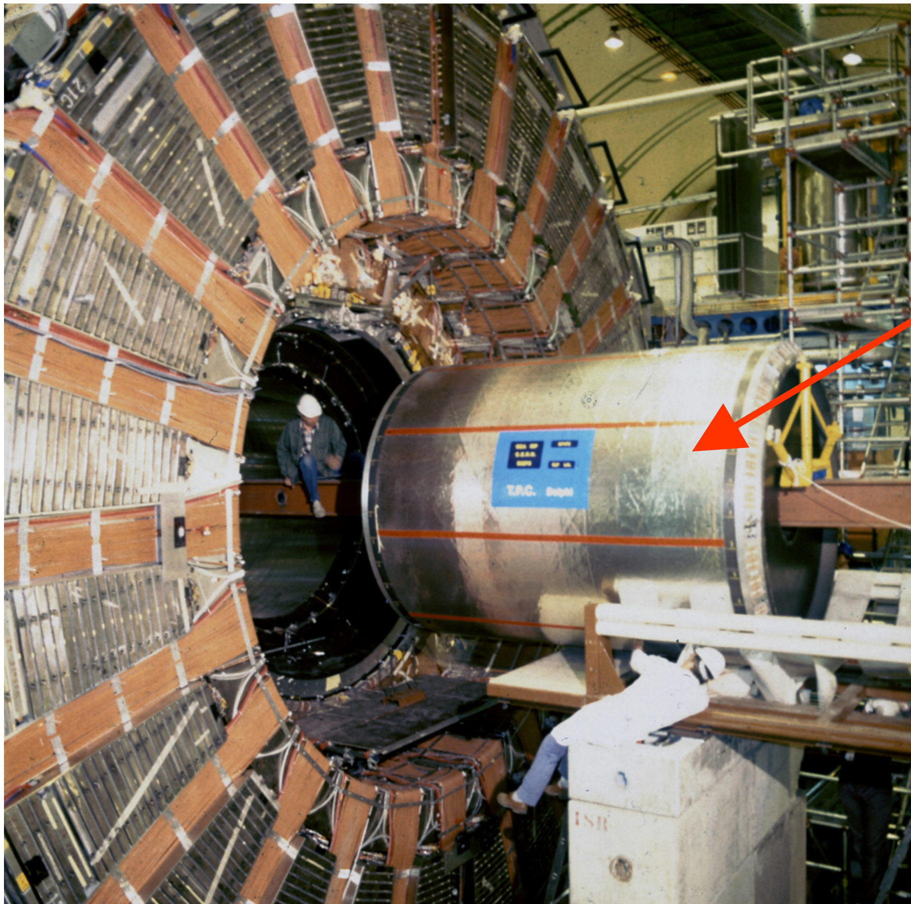



- Like a very long drift chamber, with MWPC at end (one chamber fills full tracking region)
- Accurate posn measurements and dE/ dx (long drift time)
- Signal generated by avalanche
- close to wire

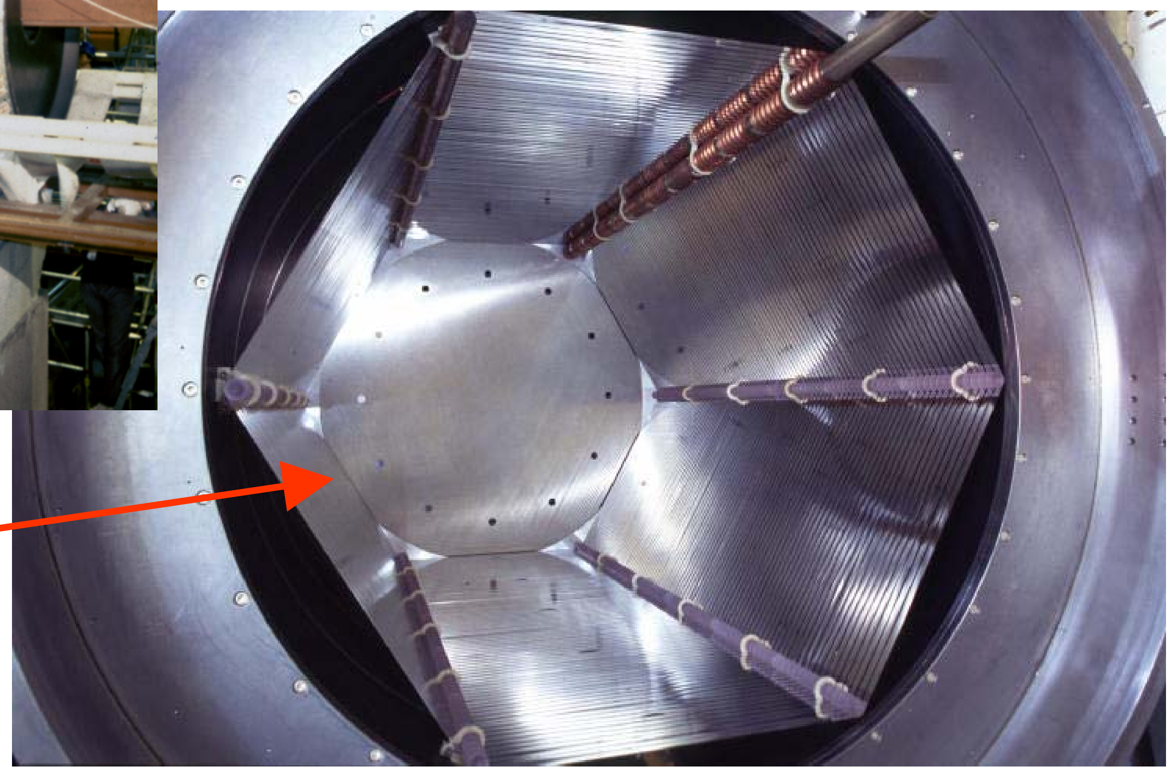



- z from drift time, x from wire number, y e.g. from perpendicular cathode pads → full 3D reconstruction ☺
- Long drift times → slow readout (typically 50 μs)
- Requires very homogeneous E, B fields → Faraday cage

# Time Projection Chamber Examples



TPC @ DELPHI (LEP)



Prototype field cage @ ALICE (LHC)

# Typical Track Detector Layout

- Gas filled detector
  - Momentum measurement
  - Many points
  - accuracy O(0.1mm)
- Semiconductor detector
  - Vertex determination
  - Few points
  - accuracy O(0.001-0.01 mm)