Why Do All Those Damned Detectors Look The Same?

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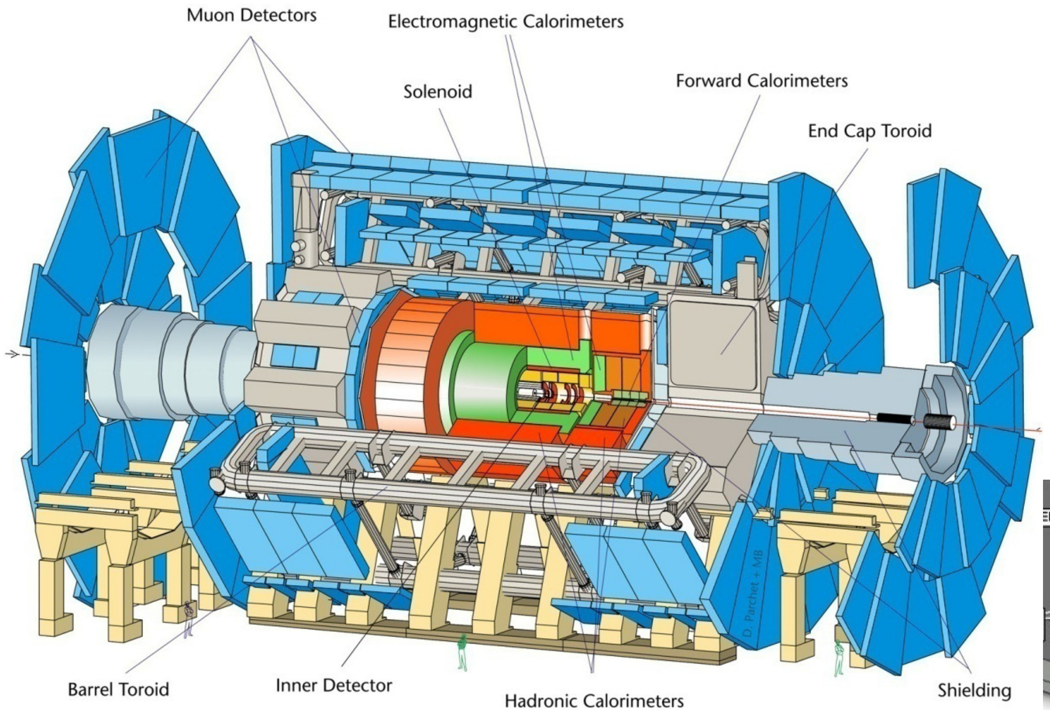
ATLAS vs PHENIX vs ….



ATLAS

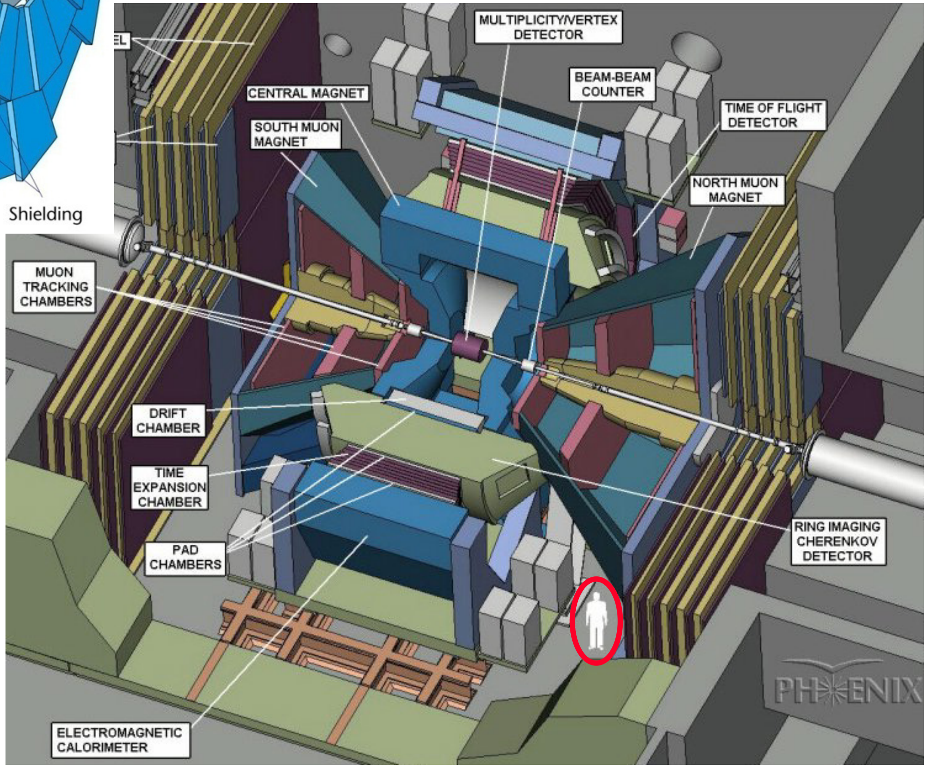
They are about the same size

They are about the same shape

Are they really different?

Even fixed target detectors look like an angular slice of one of these detectors

PHENIX



References

Outstanding References

- **Fabio Sauli’s lecture notes on wire chambers (CERN 77-09)**

- **Particle Properties Data Booklet**
  - **Particle properties**
  - **Excellent summaries of particle detection techniques**
  - **http://pdg.lbl.gov to view the pages or order your own copy**

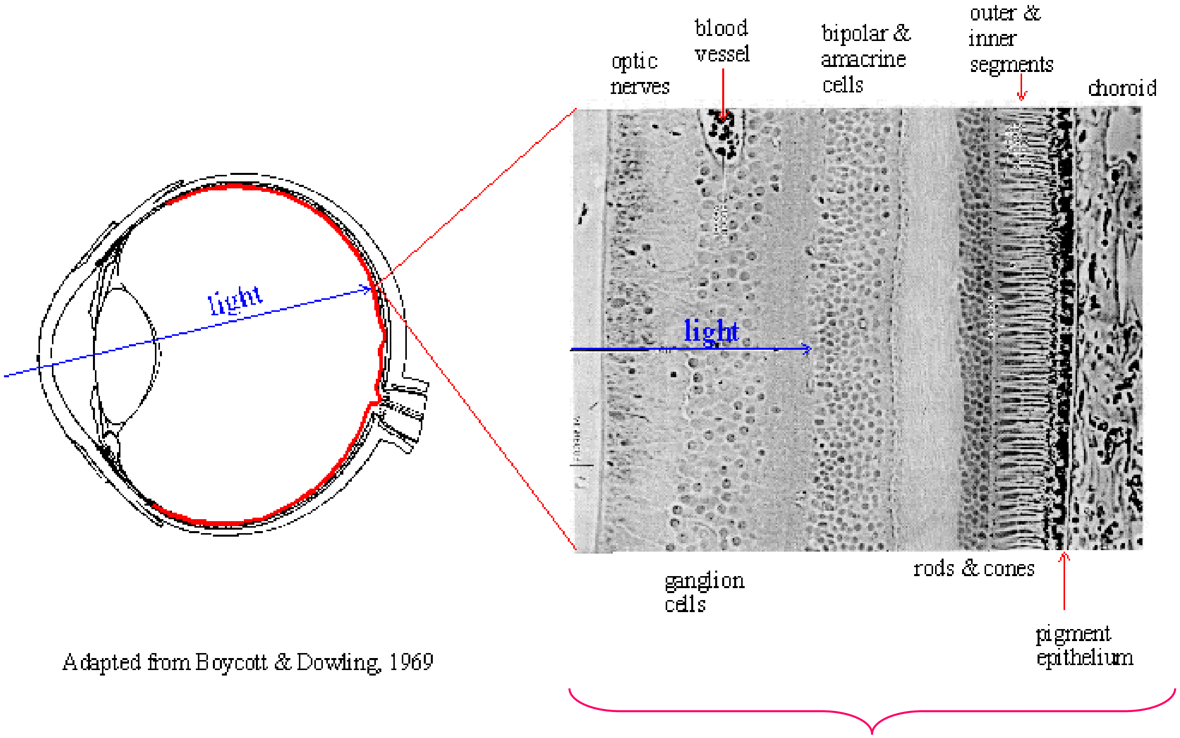
- **W. Blum, W. Riegler and L. Rolandi, “Particle Detection with Drift Chambers”, Springer, 2008.**

This talk relied heavily on additional resources from the Web

- **C. Joram – CERN Summer Student Lectures 2003**
- **T.S. Verdee – SUSSP 2003**
- **S. Stapnes – CERN School of Phyics 2002**

The Oldest Particle Detector – and a good one, too.

- **High sensitivity to photons**
- **Good spatial resolution**
- **Large dynamic range 1:10^{14}**
- **(Once upon a time) Used to tune cyclotron beams via scintillation light**

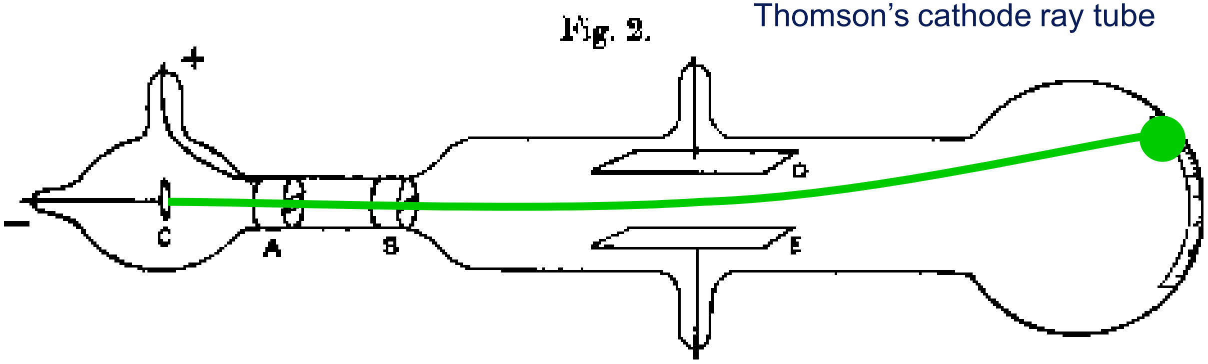


Adapted from Boycott & Dowling, 1969

retina

What should a particle detector do?

J. Plücker 1858 → J.J. Thomson 1897



Thomson’s cathode ray tube

accelerator

manipulation
By E or B field

detector

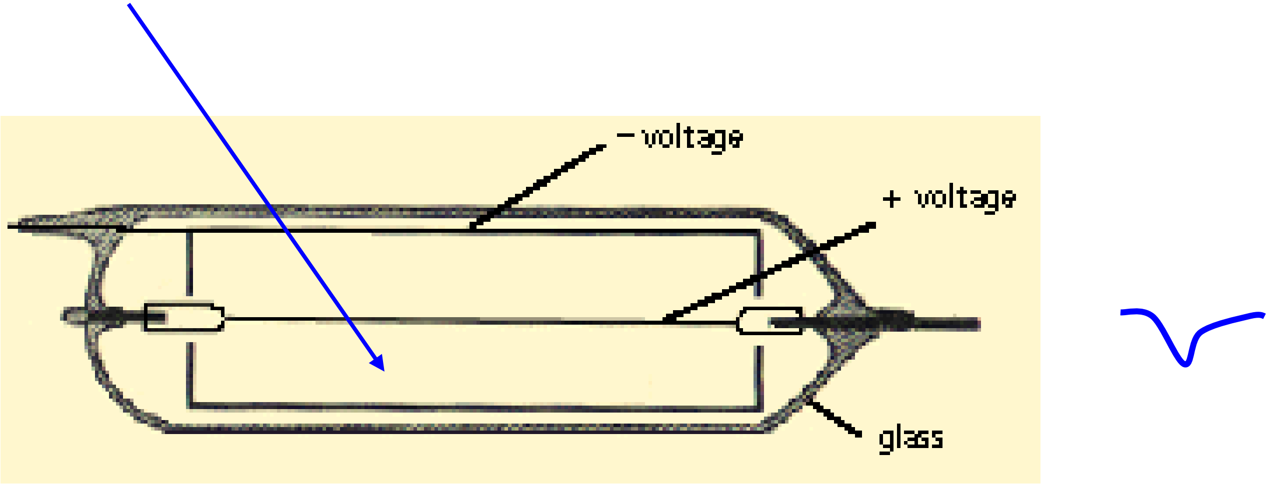
- **Note the scale pasted on the outside of the tube!**
- **Glass scintillates and we “see” the effect on the electron beam**
- **Today … mean p_T is 500 MeV so we need a meter of steel and concrete to stop the particle and make a total energy measurement.**

First electrical signal from a particle

E. Rutherford

1909

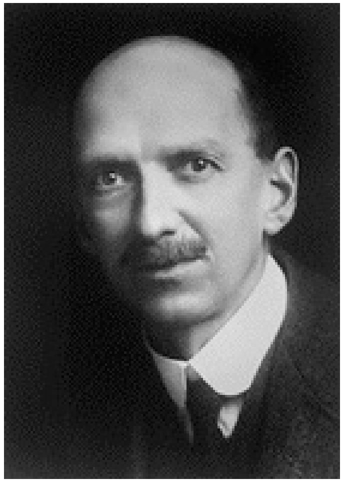
H. Geiger



The Geiger counter

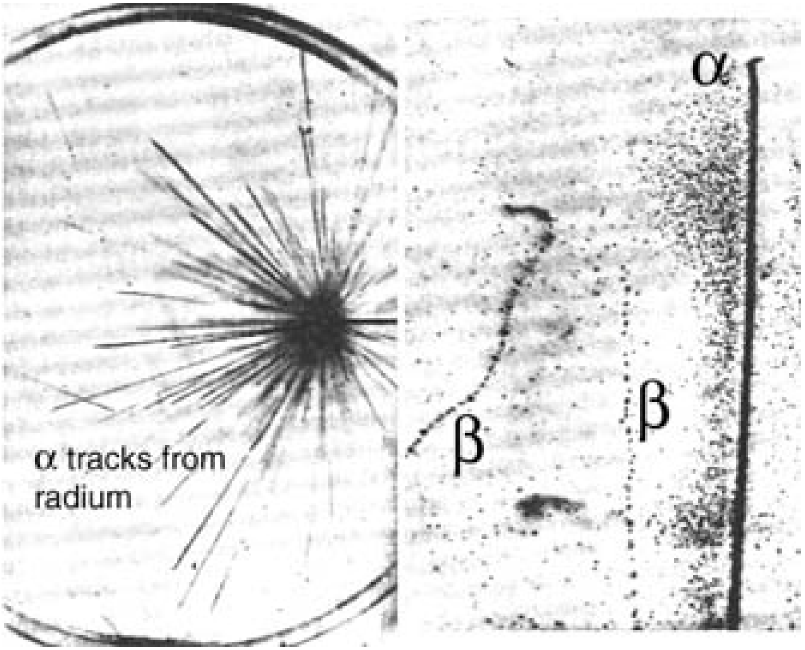
The geiger counter, and similar detectors, were used by Rutherford, Geiger, Marsden, and Royes to formulate the concept of the Rutherford atom. The electric charge is separated into a positive core and a negative cloud far outside of the core.

First tracking detector

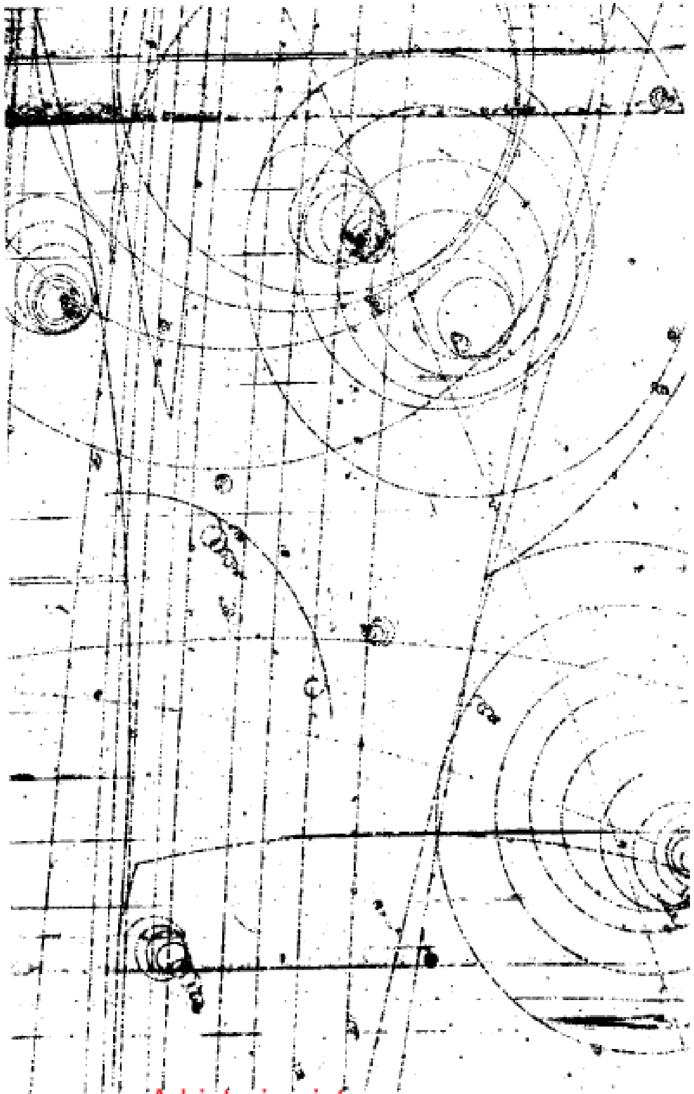


C. T. R. Wilson,
1912, Cloud chamber

The general procedure was to allow water to evaporate in an enclosed container to the point of saturation and then lower the pressure, producing a super-saturated volume of air. Then the passage of a charged particle would condense the vapor into tiny droplets, producing a visible trail marking the particle's path.



Detector Systems: Bubble Chambers



CSS00

A historic picture

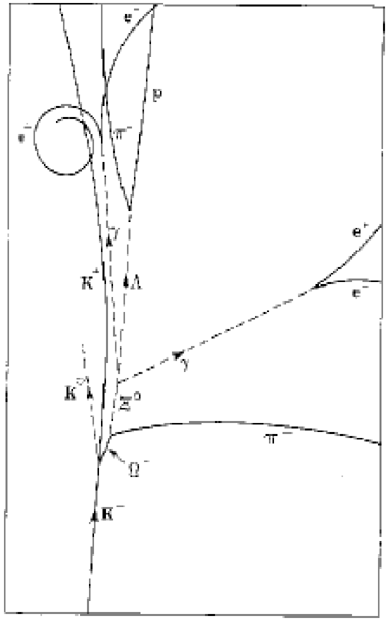
1964 : Production and decay of an Ω baryon

$$K^- p \rightarrow K^0\, \Omega^-\, K^+$$

$$\Omega^- \rightarrow \Xi^0\, \pi^-$$

$$\Xi^0 \rightarrow \Lambda^0\, \pi^0$$

$$\pi^0 \rightarrow \gamma\, \gamma$$



The Bubble chamber was Invented in 1952 by Donald Glaser … who was inspired by watching bubbles in a glass of Beer and even used Beer in his early prototypes.

Detector Philosophy

- Particles are detected by their interaction with matter

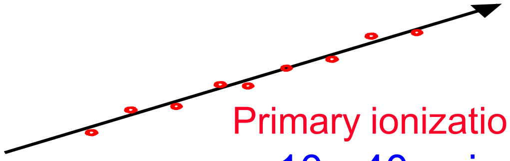
- Many different physical principals are involved
  - Electromagnetic
  - Weak
  - Strong
  - Gravity

- Most detection techniques rely on the EM interaction
  - Although, all four fundamental forces are used to measure and detect particles

- Ultimately, we observe ionization and excitation of matter.
  In this day and age, it always ends up as an electronic signal.

Ionization of gases

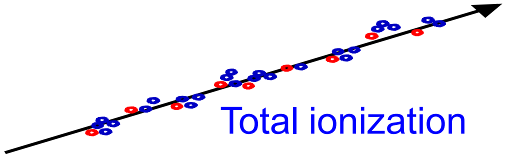
Fast charged particles ionize the atoms of a gas.



Primary ionization

10 - 40 pairs/cm

ΔE/pair ~ 25 eV

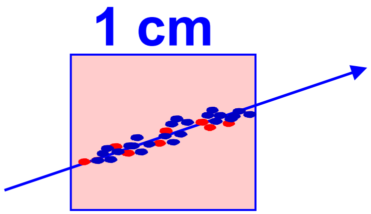


Total ionization

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

Assume detector, 1 cm thick, filled with Ar gas:



1 cm

~ 100 e-ion pairs

100 electron-ion pairs are not easy to detect!

Noise of amplifier ≈ 1000 e^- (ENC) !

We need to increase the number of e-ion pairs.

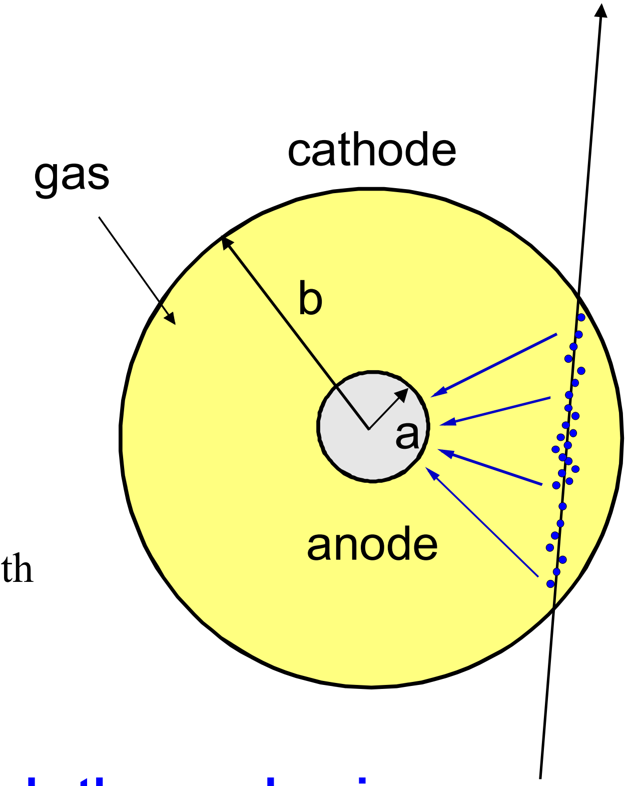
Gas Amplification in a Proportional Counter

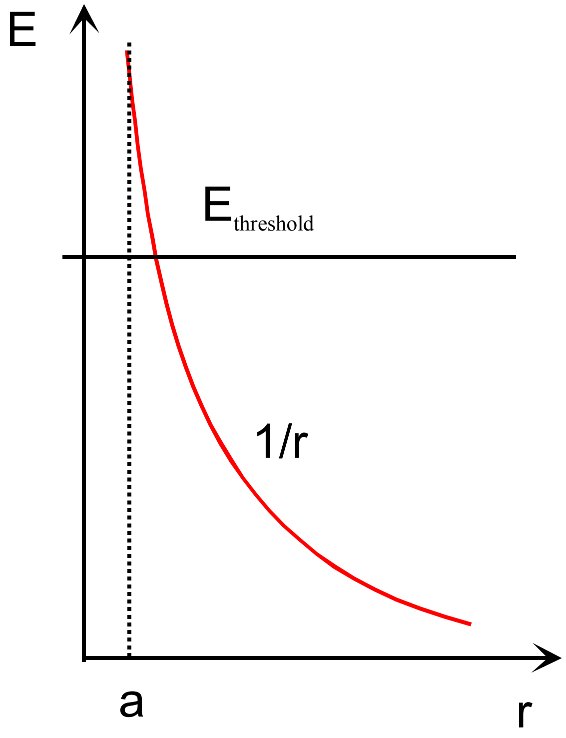
Consider cylindrical field geometry (simplest case):

$$E(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\varepsilon_0} \cdot \ln\frac{r}{a}$$

C = capacitance / unit length



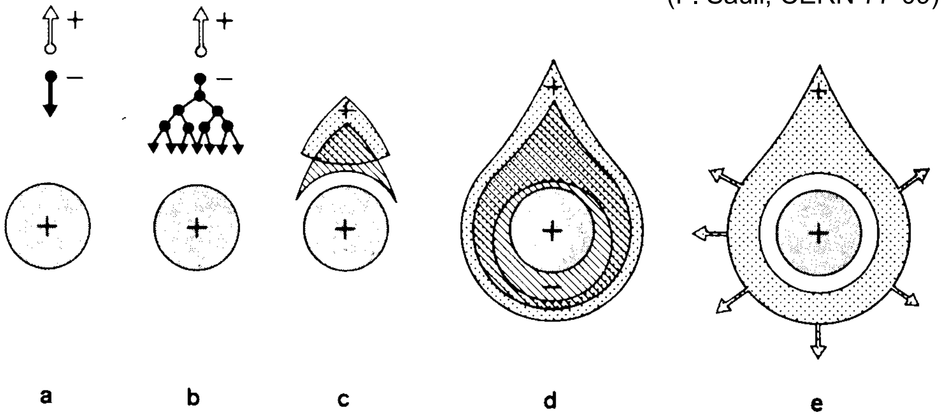


Electrons drift towards the anode wire

Close to the anode wire the electric field is sufficiently high (kV/cm), that the e$^-$ gain enough energy for further ionization → <u>exponential increase</u> in the number of e$^-$-ion pairs.

Signal Formation - Proportional Counter

(F. Sauli, CERN 77-09)

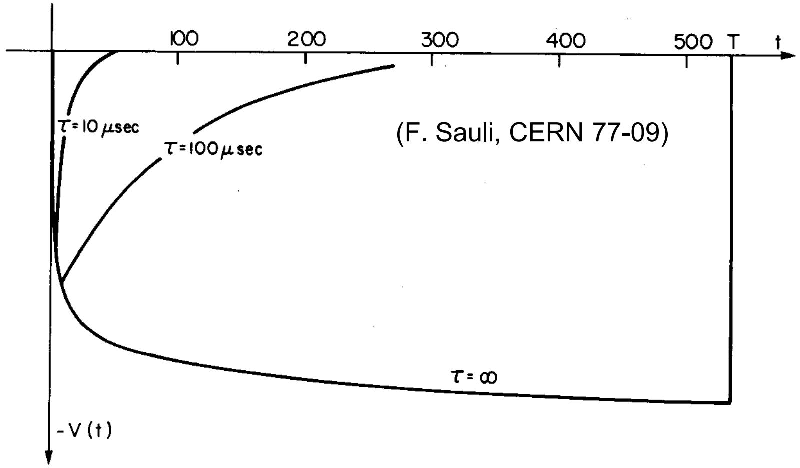


Avalanche form within a few radii or the wire and within t < 1 ns!

Signal induction both on anode and cathode due to moving charges (both electrons and ions).

$$dv = \frac{Q}{lCV_0}\frac{dV}{dr}dr$$

Electrons are collected on the anode wire, (i.e. *dr* is small, only a few μm). Electrons contribute only very little to detected signal (few %).



(F. Sauli, CERN 77-09)

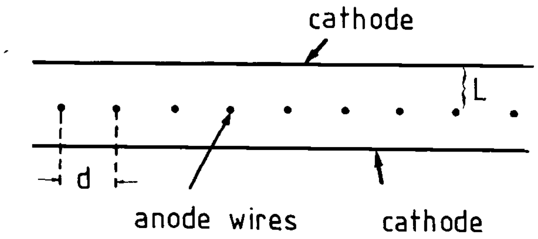
Ions have to drift back to cathode, i.e. *dr* is big. Signal duration limited by total ion drift time !

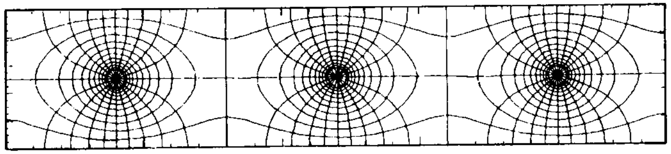
We need electronic signal differentiation to limit dead time.

Multiwire Proportional Chamber

Multi wire proportional chamber (MWPC)

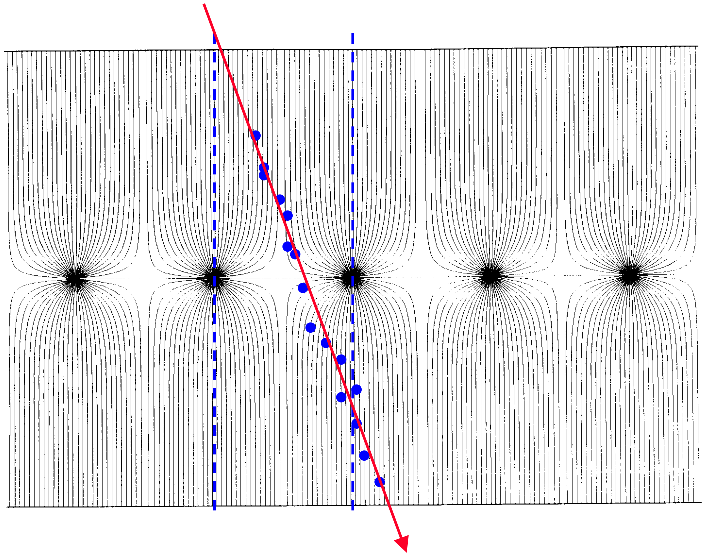
(G. Charpak et al. 1968, Nobel prize 1992)





field lines and equipotentials around anode wires

Address of fired wire(s) only give 1-dimensional information. This is sometimes called "Projective Geometry". It would be better to have a second dimension ….



Typical parameters:

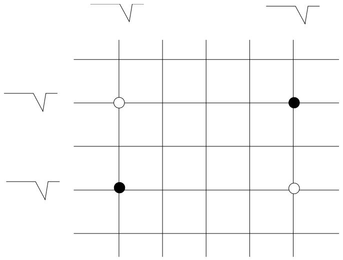
$L = 5\text{mm}$, $d = 1\text{mm}$, $r_{wire} = 20\mu\text{m}$.

Normally digital readout:
spatial resolution limited to

$$\sigma_x \approx \frac{d}{\sqrt{12}}$$

(d=1mm, σ_x=300 µm)

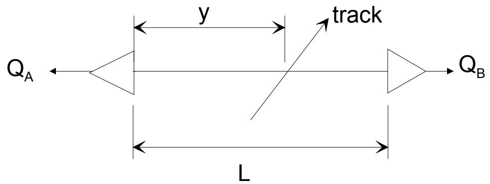
The Second Dimension … 2D readout



Crossed wire planes. Ghost hits. Restricted to low multiplicities.

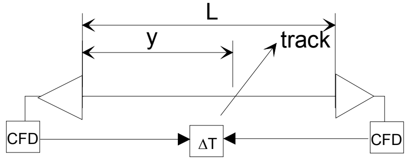
90 degrees or stereo planes crossing at small angle.

Charge division: Resistive wires (Carbon,2kΩ/m).



$$\frac{y}{L} = \frac{Q_B}{Q_A + Q_B} \qquad \sigma\left(\frac{y}{L}\right) \text{ up to } 0.4\%$$

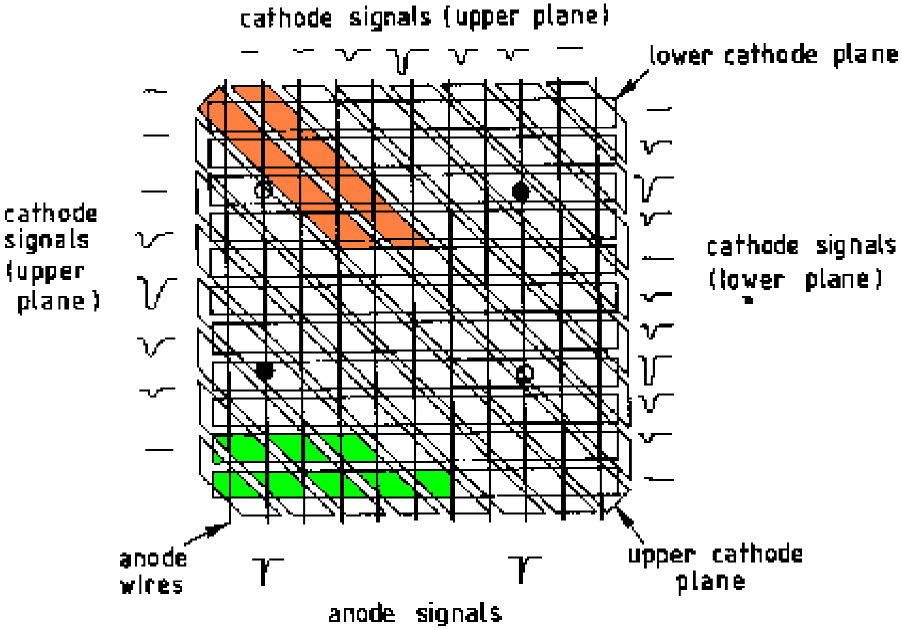
Timing difference:



$$\sigma(\Delta T) = 100\,ps$$
$$\rightarrow \ \sigma(y) \approx \ few\ cm$$

Segmented cathode planes:

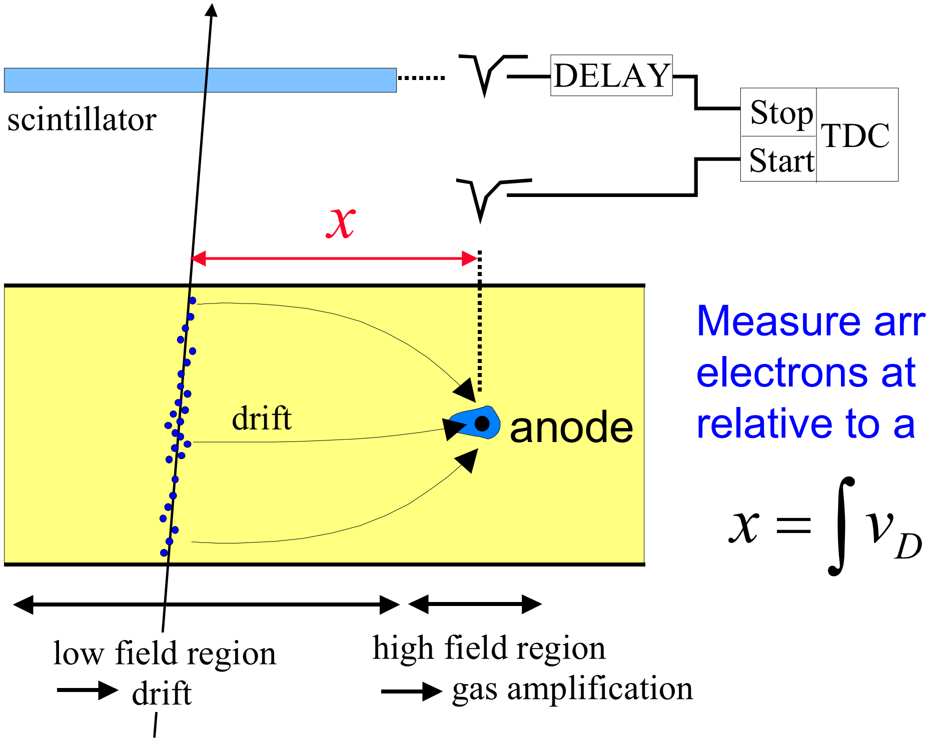
Analog readout of cathode planes $\rightarrow \sigma \approx 100\ \mu\text{m}$



The Third Dimension: Timing Difference

Drift Chambers :

- **Reduced numbers of readout channels**
- **Distance between wires typically 5-10cm giving around 1-2 μs drift-time**
- **Resolution of 50-100μm achieved limited by field uniformity and diffusion**
- **Perhaps problems with <u>occupancy</u> of tracks in one cell.**



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

$$x = \int v_D(t)\,dt$$

(First studies: T. Bressani, G. Charpak, D. Rahm, C. Zupancic, 1969
First operation drift chamber: A.H. Walenta, J. Heintze, B. Schürlein, NIM 92 (1971) 373)

Drift and Diffussion in Gases

Without external fields:

Electrons and ions will lose their energy due to collisions with the gas atoms → thermalization

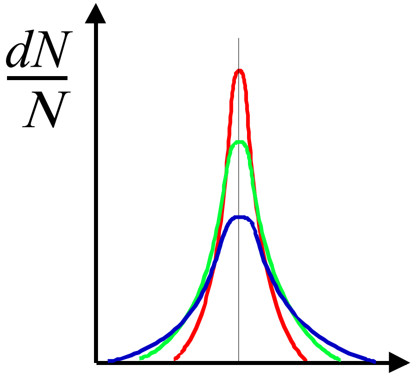
$$\varepsilon = \frac{3}{2} kT \approx 40 \text{ meV}$$

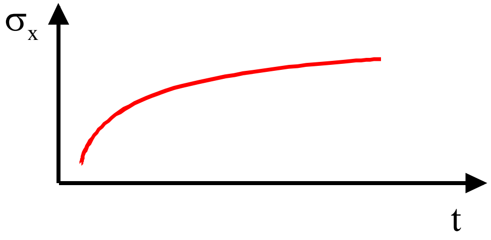
Undergoing multiple collisions, a localized ensemble of charges will diffuse

$$\frac{dN}{N} = \frac{1}{\sqrt{4\pi Dt}} e^{-(x^2/4Dt)}\, dx$$

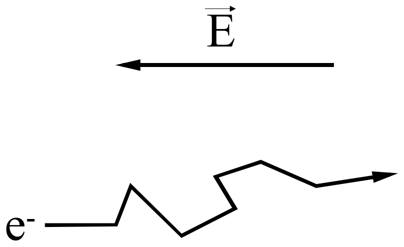
$$\sigma_x(t) = \sqrt{2Dt} \qquad or \quad D = \frac{\sigma_x^2(t)}{2t}$$

D: diffusion coefficient





With External electric field:



multiple collisions due to
scattering from gas atoms → drift

$$\vec{v}_D = \mu \vec{E} \qquad \mu = \frac{e\tau}{m} \ \text{(mobility)}$$

Typical electron drift velocity: **2 to 5 cm/μs**

Ion drift velocities are ~1000 times smaller

3D: The Time Projection Chamber

Time Projection Chamber → full 3-D track reconstructic

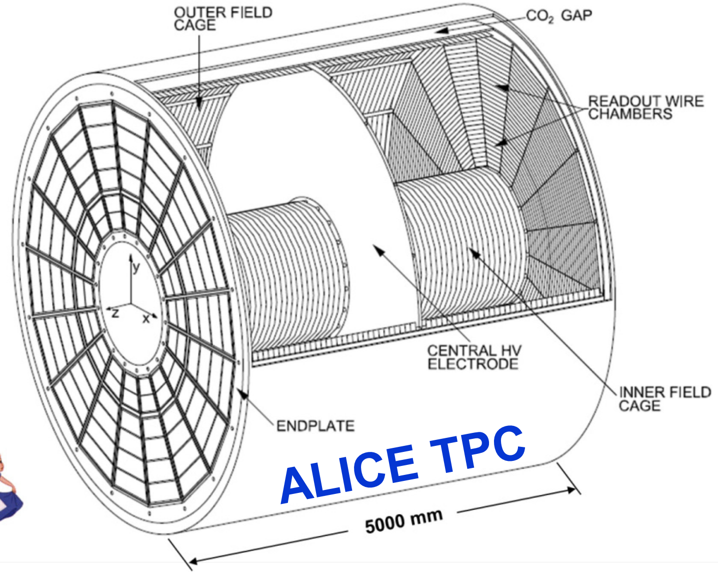
- x-y from wires and segmented cathode of MWPC
- z from drift time
- in addition dE/dx information

Diffusion significantly reduced by B-field.

Requires precise knowledge of v_D →
LASER calibration + p,T corrections

Drift over long distances → very good gas quality required

Space charge problem from positive ions, drifting back to midwall → use a gated grid



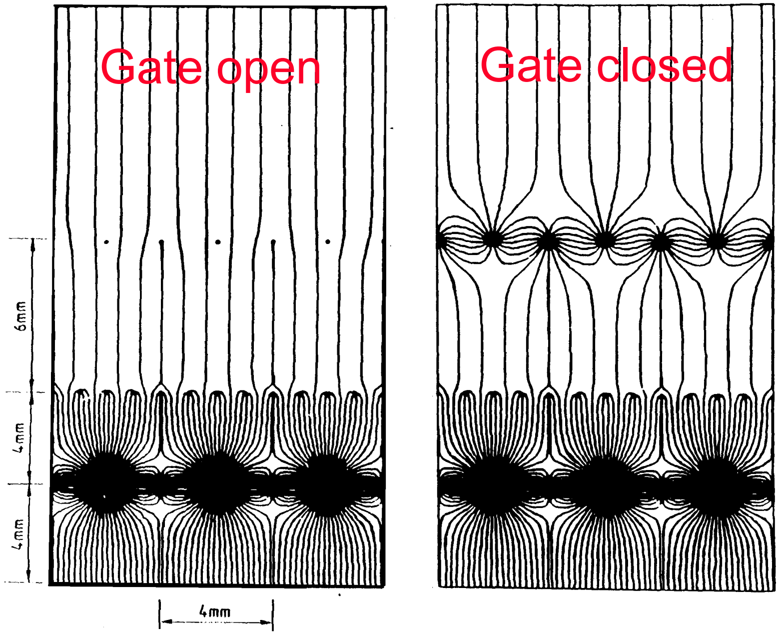
ALEPH TPC

(ALEPH coll., NIM A 294 (1990) 121,
W. Atwood et. Al, NIM A 306 (1991) 446)

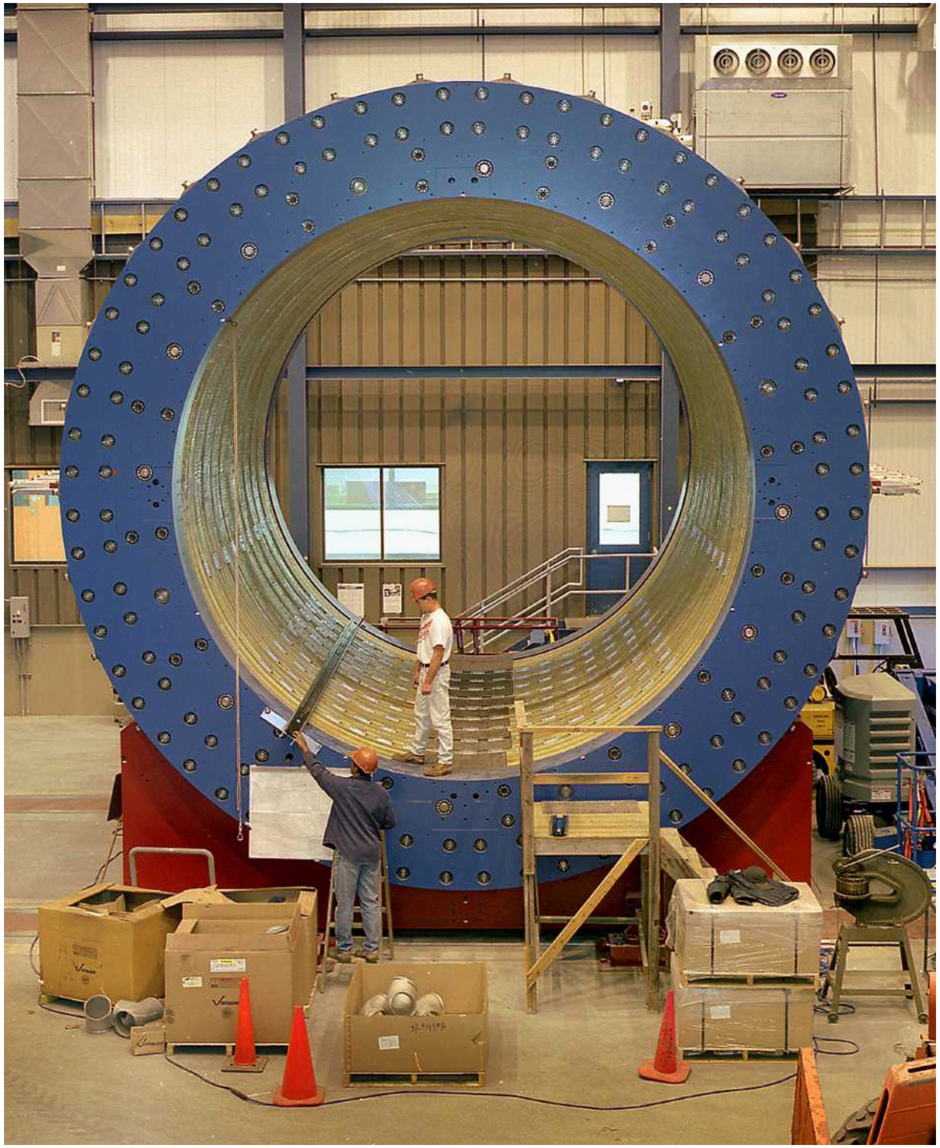
Ø 3.6M, L=4.4 m

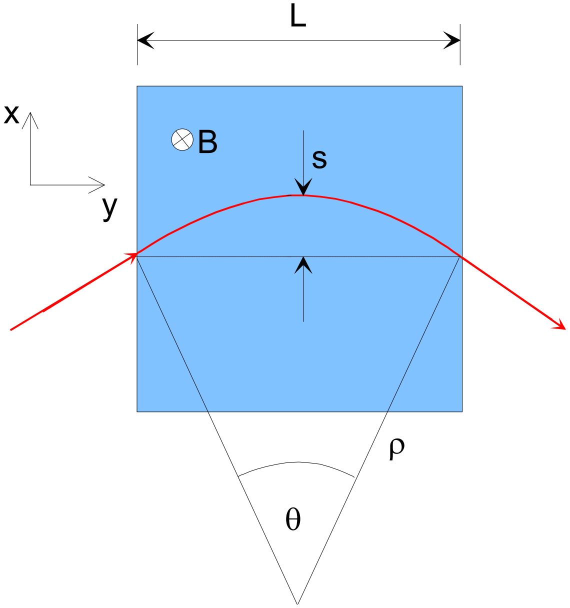
ΔV_g = 150 V

$\sigma_{R\phi} = 173\ \mu m$
$\sigma_z = 740\ \mu m$
(isolated leptons)



The STAR Magnet (room temp Aluminum coils)





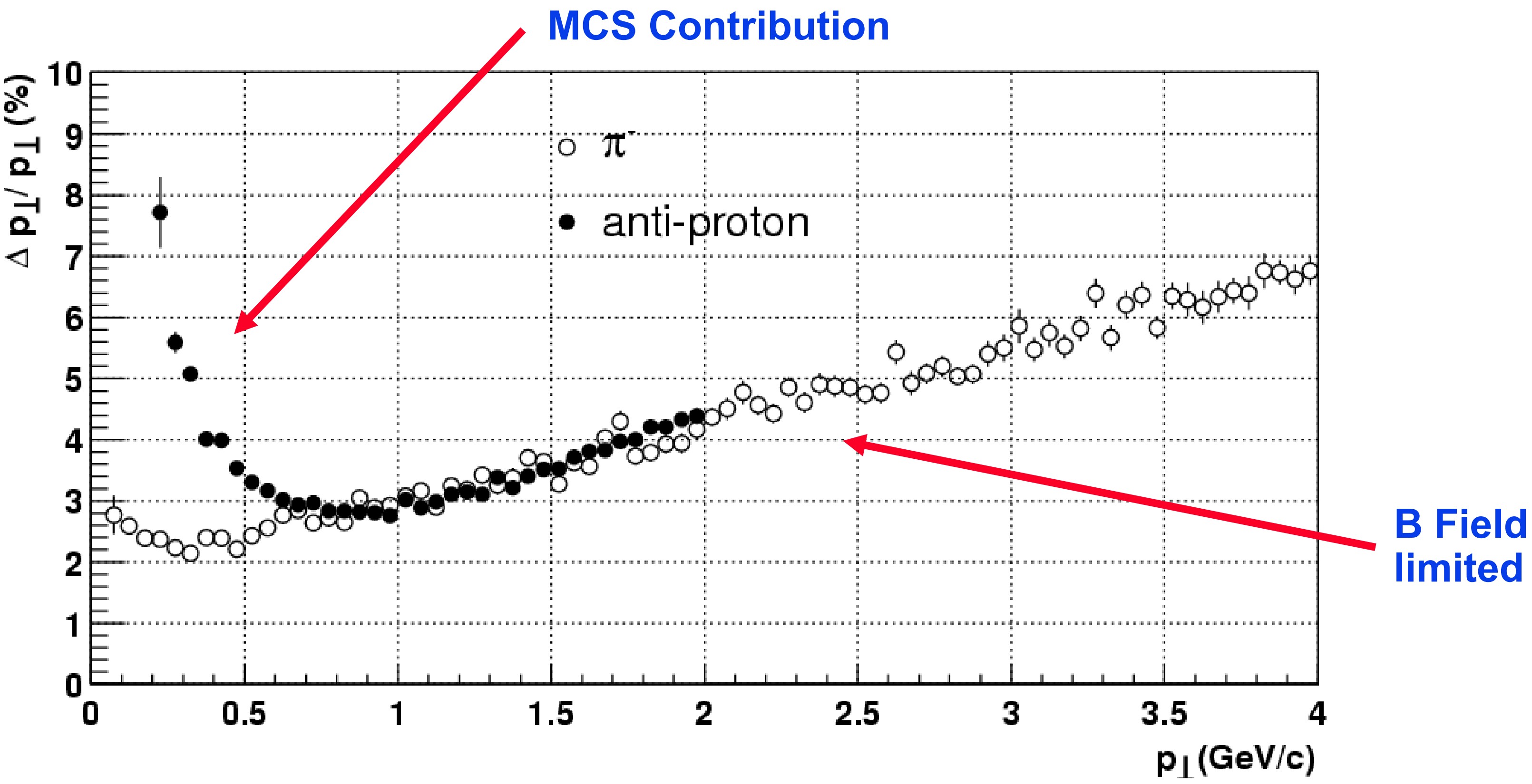
A charged particle in a uniform field follows a (perfect) circular path

$$m\frac{d\overline{\mathrm{v}}}{dt} = q\left(\overline{\mathrm{v}}\times\overline{B}\right) \rightarrow \frac{m\,\mathrm{v}^2}{\rho} = q\left|\overline{\mathrm{v}}\times\overline{B}\right|$$

$$\frac{m\,\mathrm{v}^2}{\rho} = q\left|\overline{\mathrm{v}}\times\overline{B}\right| \rightarrow p_T = qB\rho$$

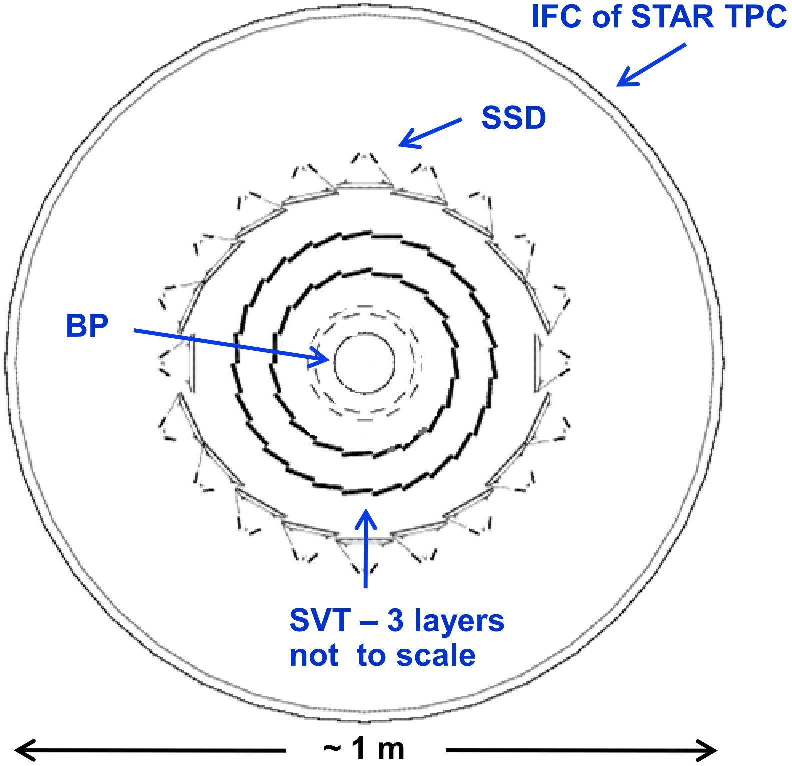
$$\boxed{p_T\ (\mathrm{GeV/c}) = 0.3B\rho \quad (\mathrm{T}\cdot\mathrm{m})}$$

Momentum Resolution: the Magnet + TPC



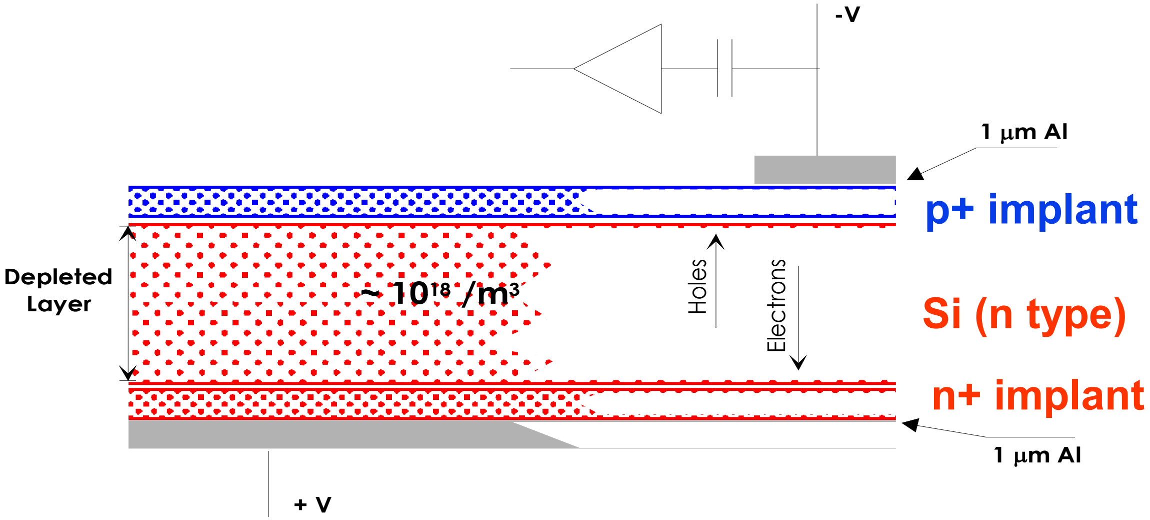
- **Momentum resolution is only limited by the strength of the magnetic field and is independent of the mass of the particle at high P_T**
- **Momentum resolution at low P_T is determined by multiple coulomb scattering (MCS)**

Several layers of Si surround the Beam Pipe

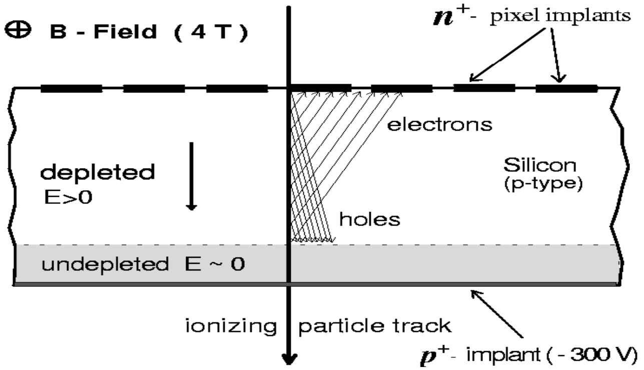


- Si provides high resolution space-points which can be added to the TPC tracks
- Improves the quality of the track
- Improves the momentum resolution
- Improves the DCA resolution and pointing at the vertex

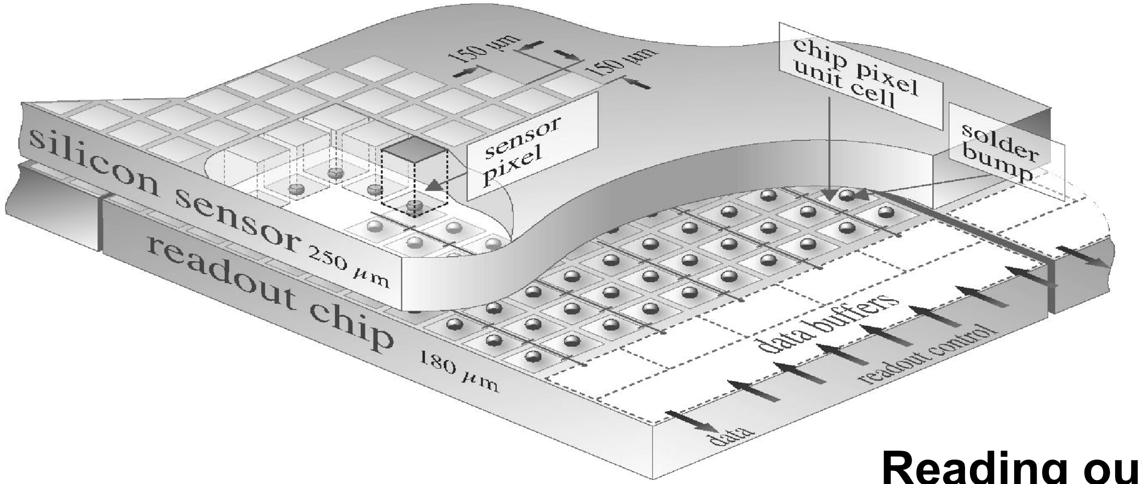
Semiconductor Detectors: Silicon



The typical Semiconductor detector is a based on a Si diode structure

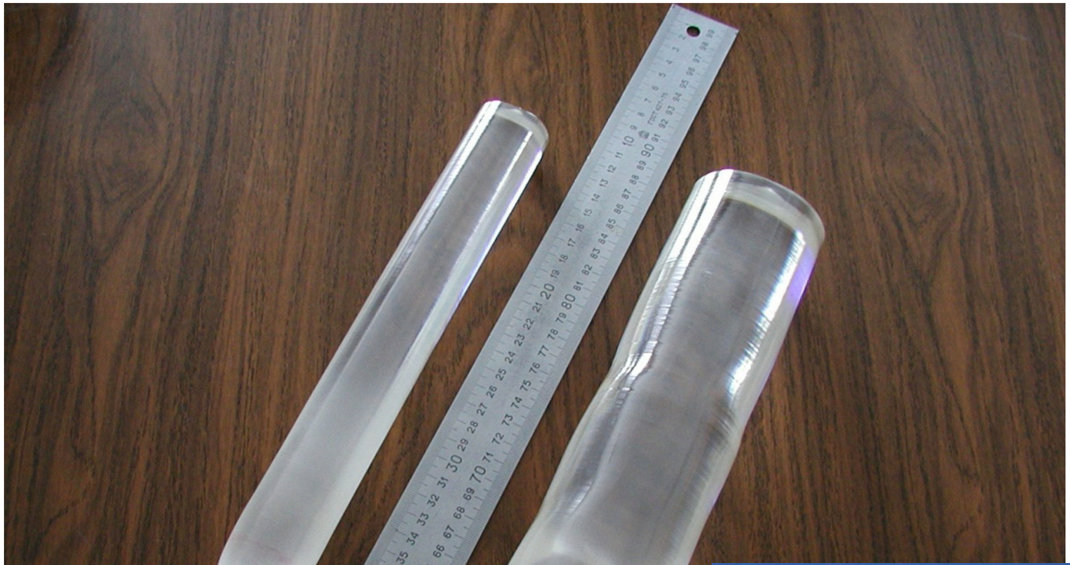


Interaction with ionizing radiation

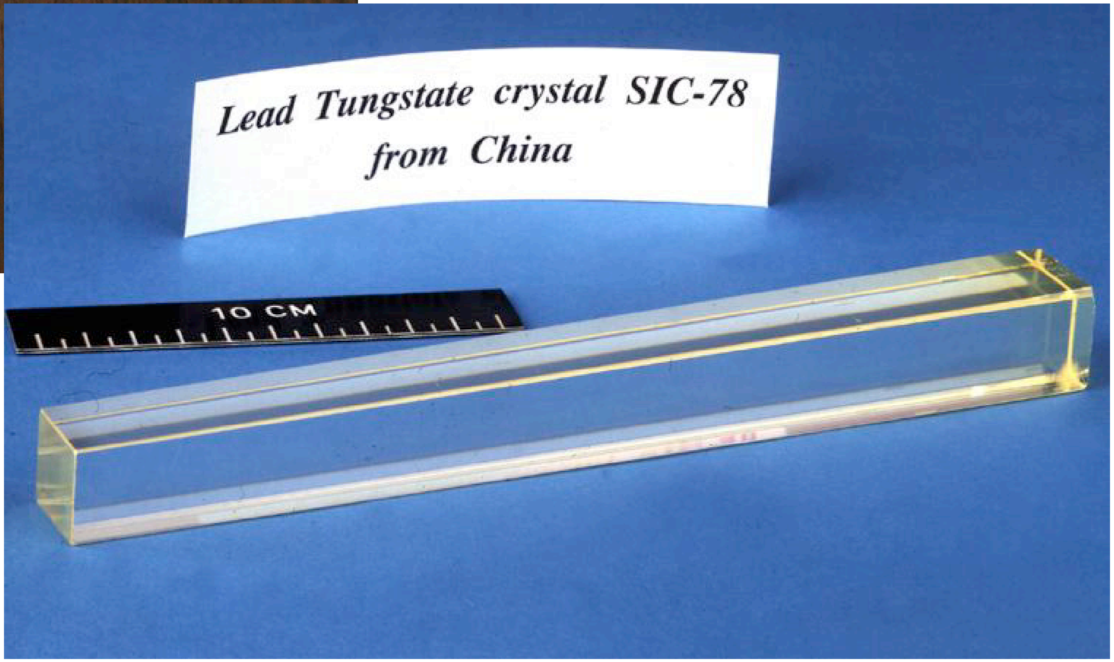


Reading out the pixels

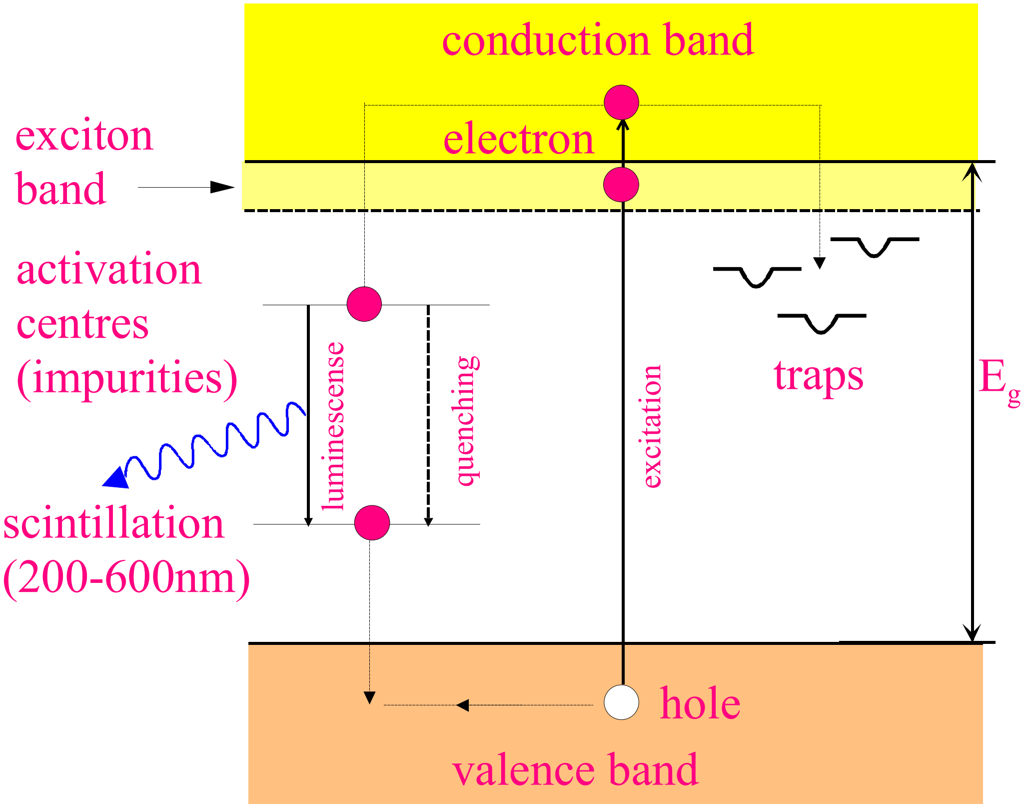
Scintillation Light: Inorganic Scintillators



PbWO$_4$ ingot and final polished CMS ECAL scintillator crystal from Bogoroditsk Techno-Chemical Plant (Russia).

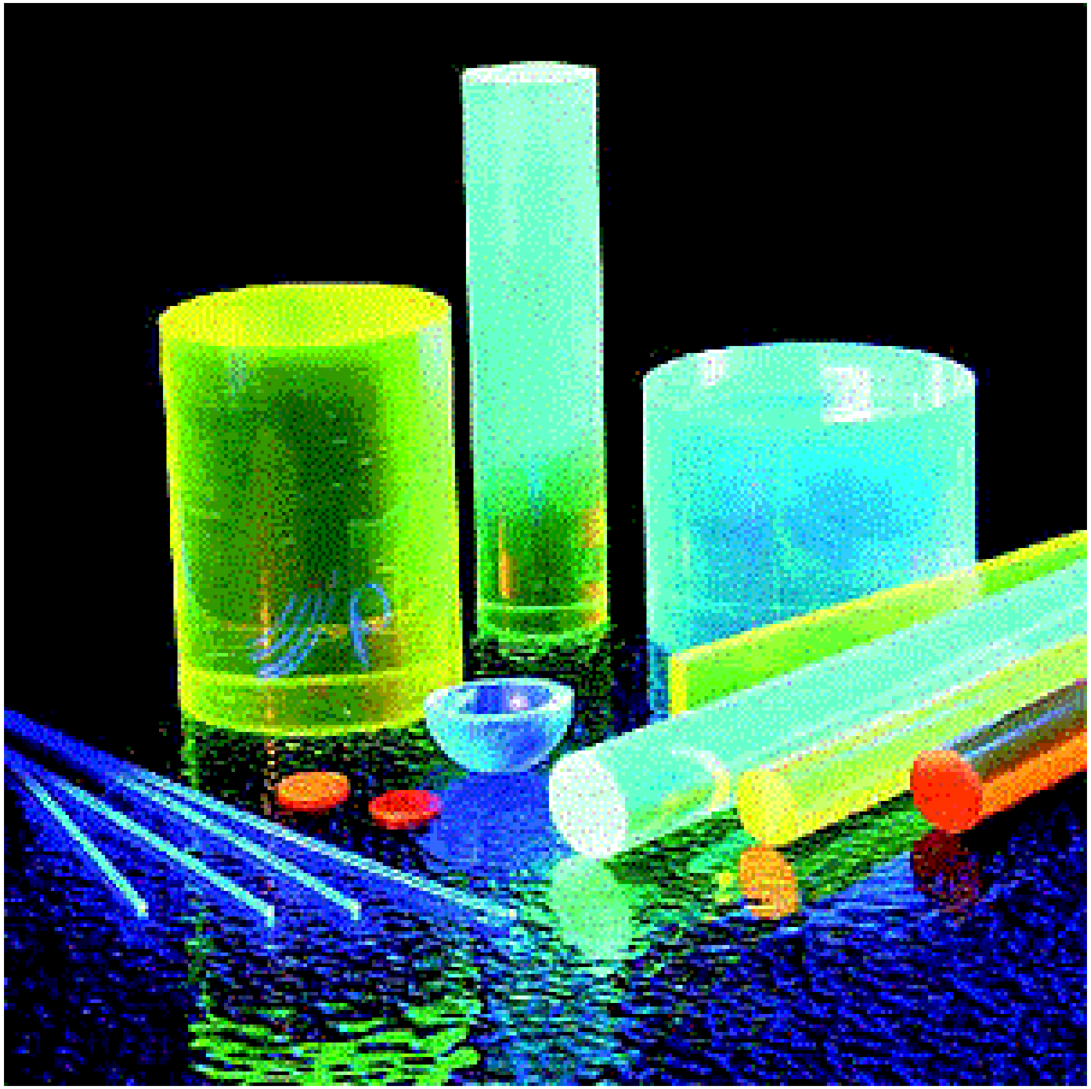


Inorganic Scintillators: NaI, BGO, $PbWO_4$, …

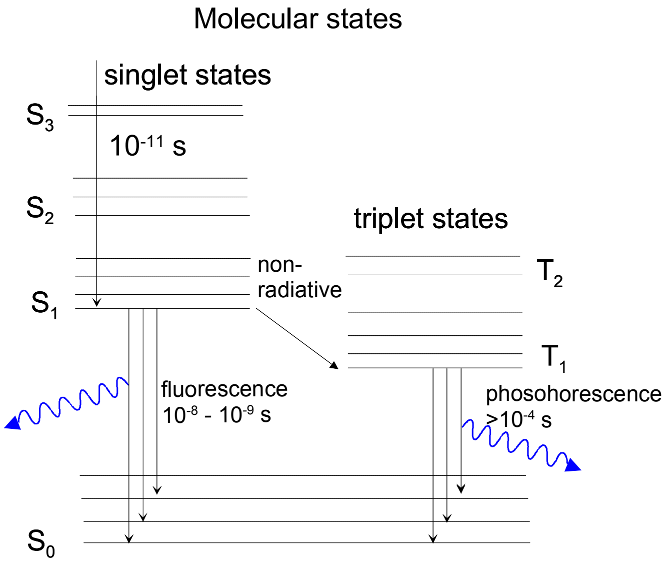


- Excitation of electrons into the conduction band allows light to be produced during relaxation to the ground state.
- Inorganic scintillators are usually high density and high Z materials
- Thus they can stop ionizing radiation in a short distance

Scintillation Light: Organic Scintillators



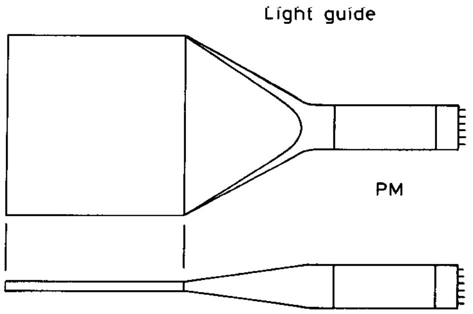
- **Liquid and plastic organic scintillators are available**
- **They normally consist of a solvent plus secondary (and tertiary) fluors as wavelength shifters.**



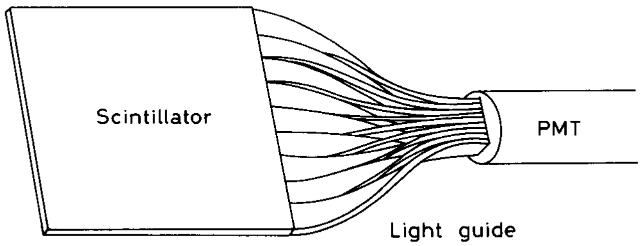
Scintillator Readout Schemes

Geometrical adaptation:

Light guides: transfer by total internal reflection (+outer reflector)



“fish tail”



adiabatic

Wavelength shifter (WLS) bars

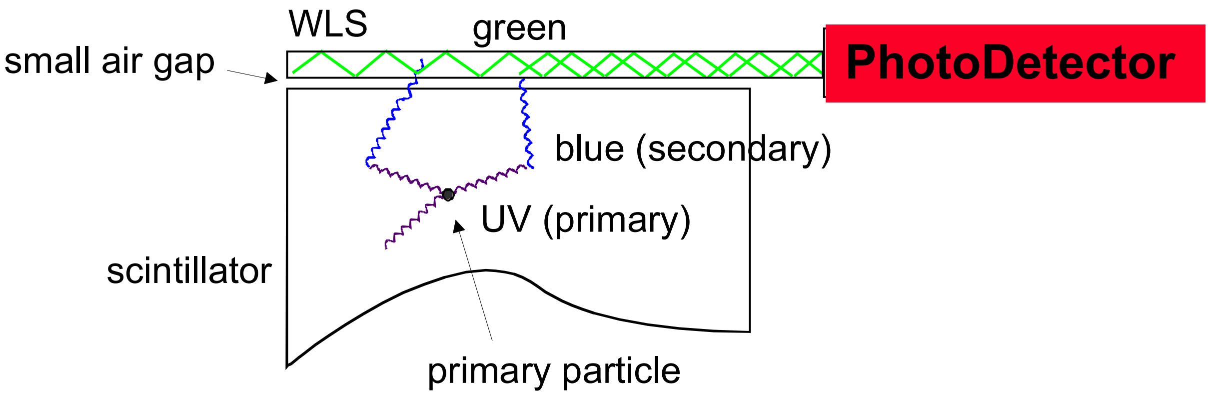
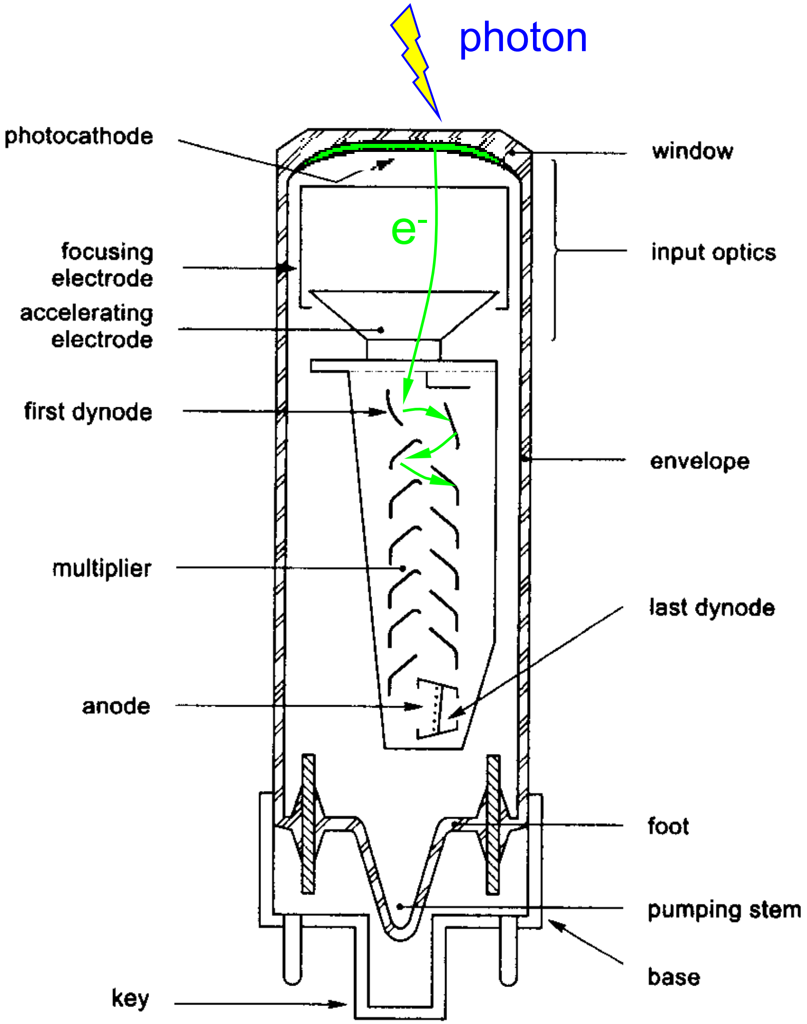


Photo Multiplier Tubes (PMT)

(Philips Photonic)



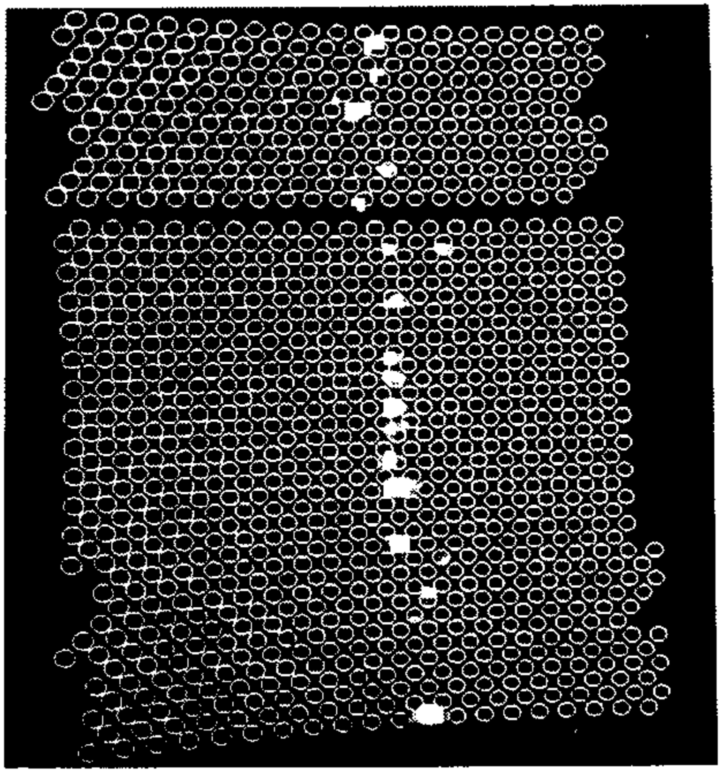
Main phenomena:

- photo emission from photo cathode.
- secondary emission from dynodes.
  dynode gain g = 3-50 (f(E))
- total gain
  10 dynodes with g=4
  $M = 4^{10} \approx 10^6$

Scintillator Applications

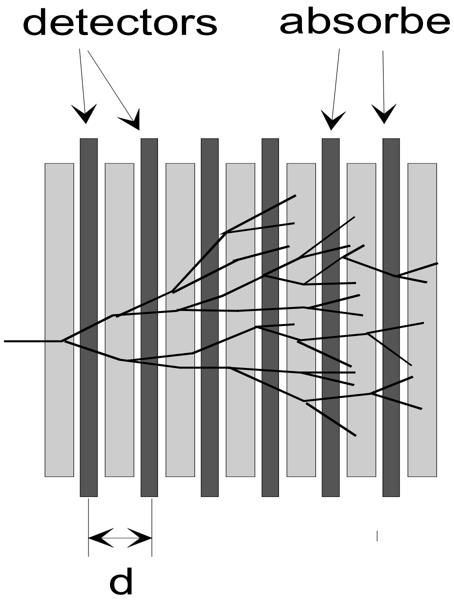
Tracking

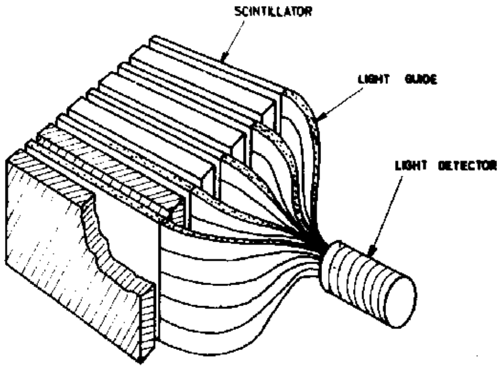
Charged particle passing through a stack of scintillating fibers (diam. 1mm)



Sampling Calorimeters

Absorber + detector separated → additional sampling fluctuations

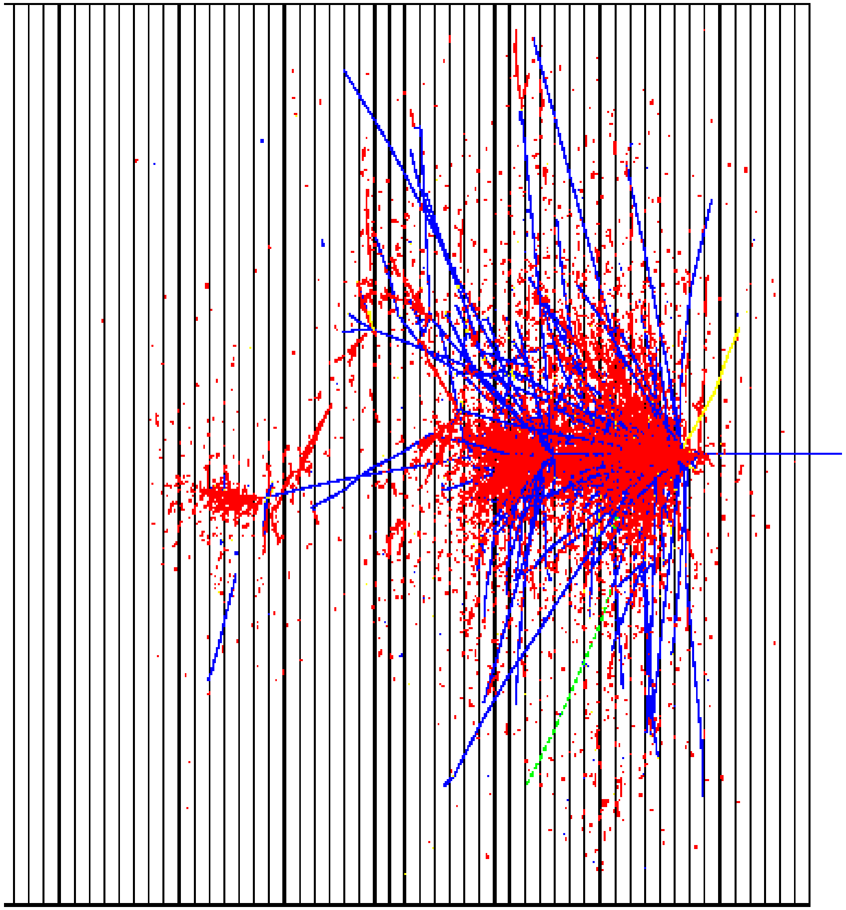


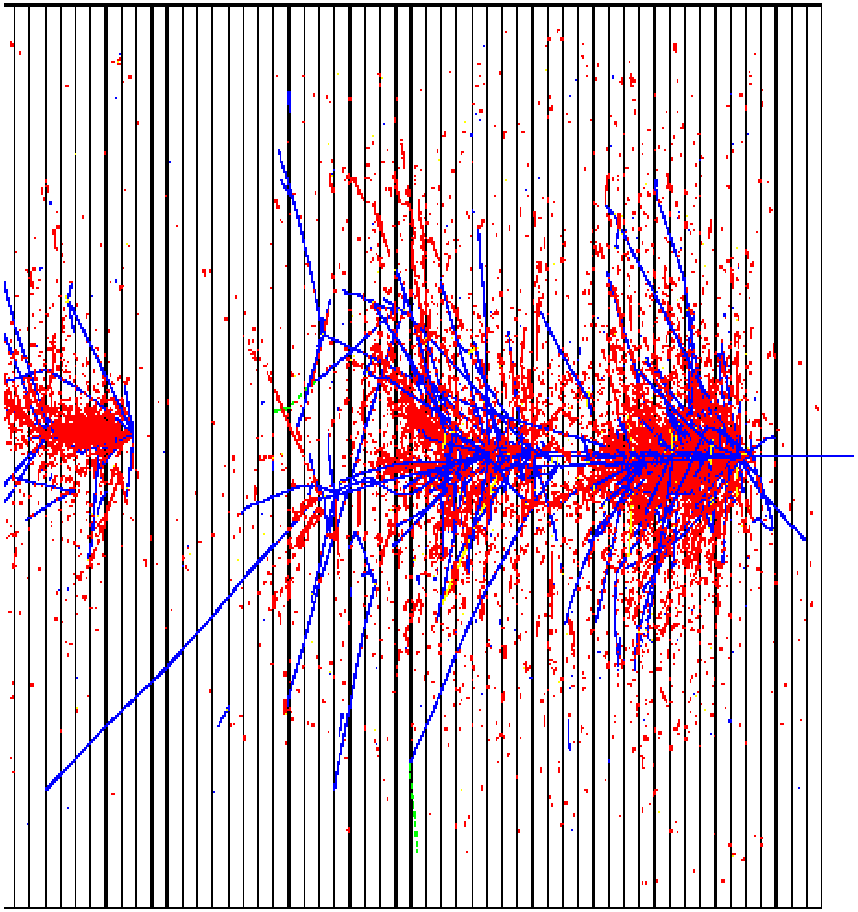


Time of Flight

Measure the time of flight of a particle between a thin, flat, “start” counter and a thin “stop” counter.

150 GeV Pion Showers in Cu





Hadron shower not as well behaved as an em one

red - e.m. component
blue - charged hadrons

Hadron calorimeter are always sampling calorimeters

Lets Design a Detector: Requirements

Very good particle identification

trigger efficiently and measure ID and momentum of all particles

High resolution electromagnetic calorimetry

Powerful inner tracking systems

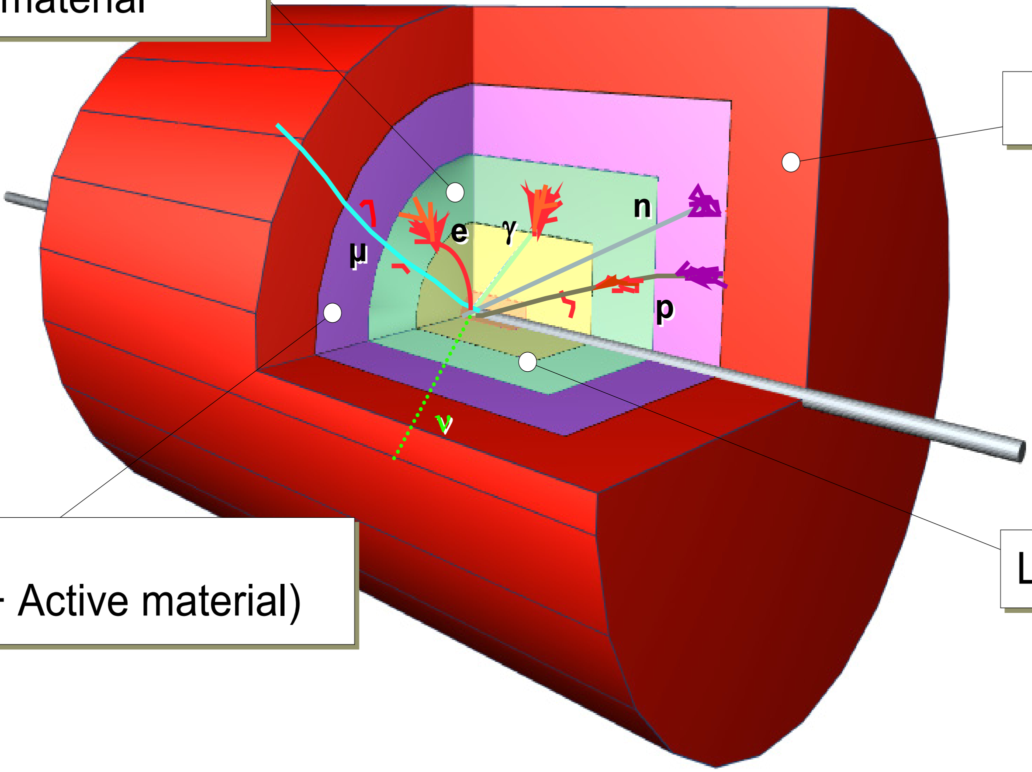
Improves momentum resolution, find tracks of short lived particles

Hermetic coverage

good rapidity coverage, good missing E_T resolution

Affordable detector

‘Cylindrical Onion-like’ Structure of HE Detectors



Materials with high number of protons + Active material

Hermetic calorimetry
- Missing Et measurements

Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing E_T)
- Energy measurement

Heavy materials

Muon detector
- μ identification

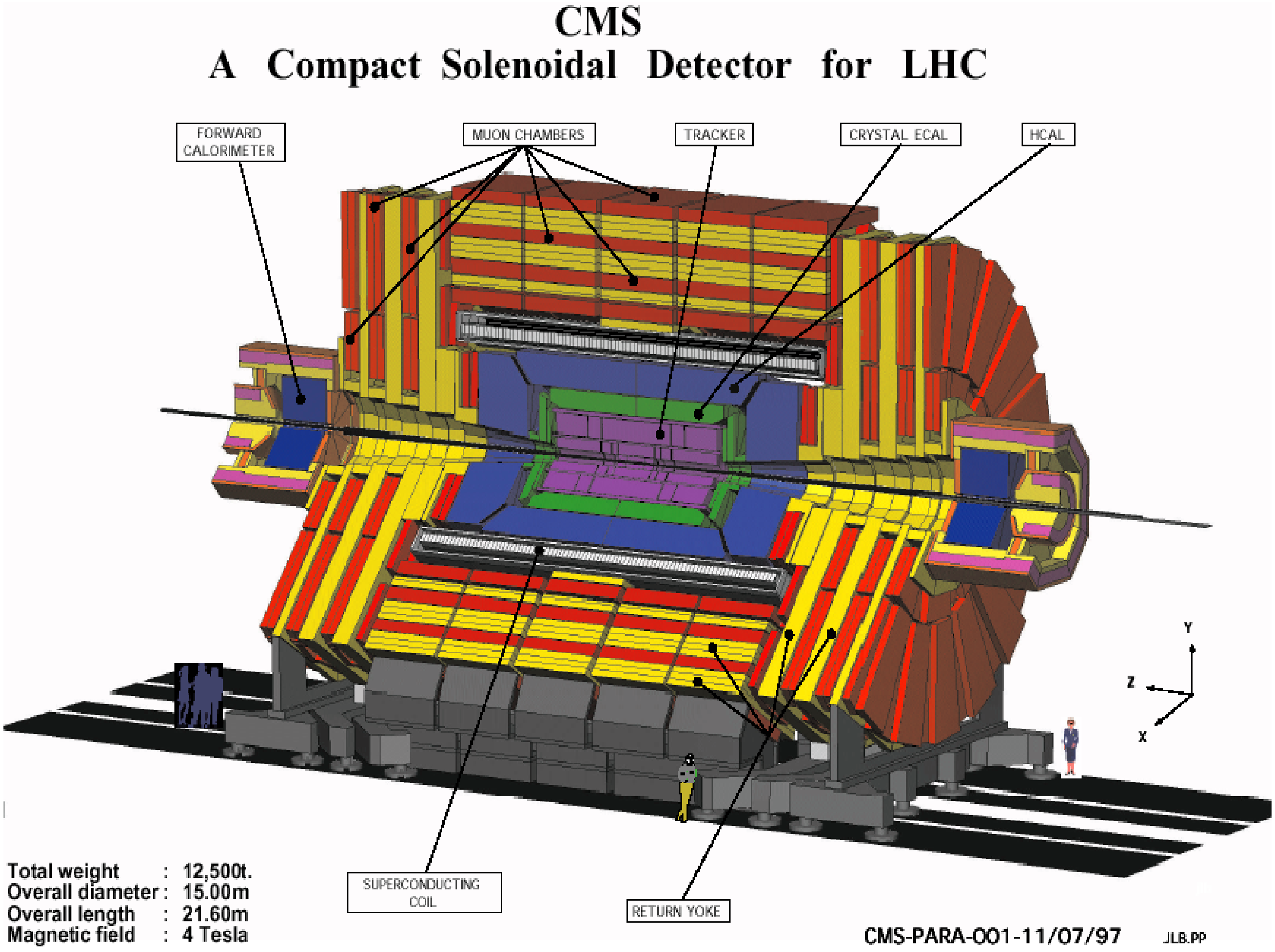
Heavy materials
(Iron or Copper + Active material)

Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

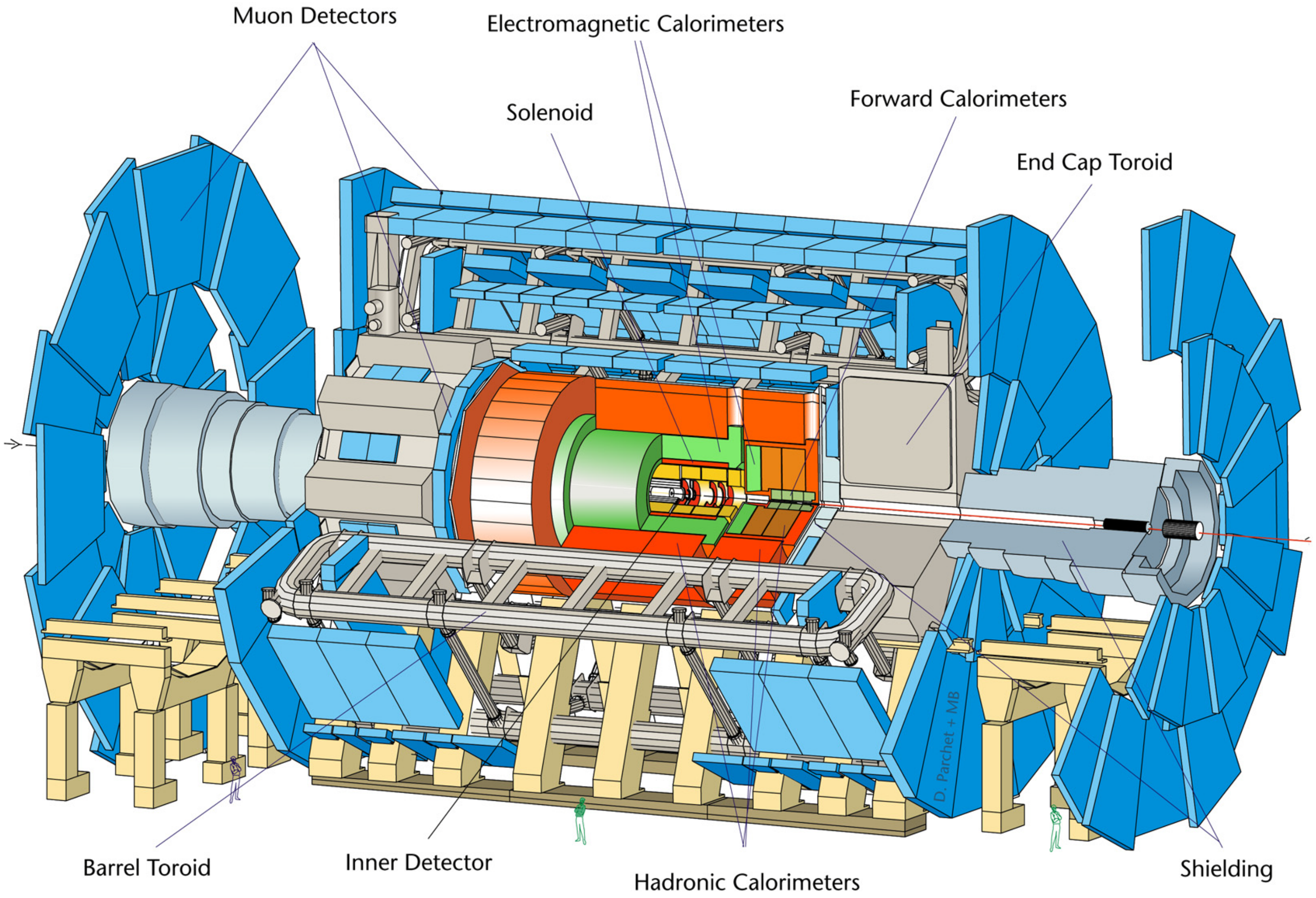
Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

The CMS Detector

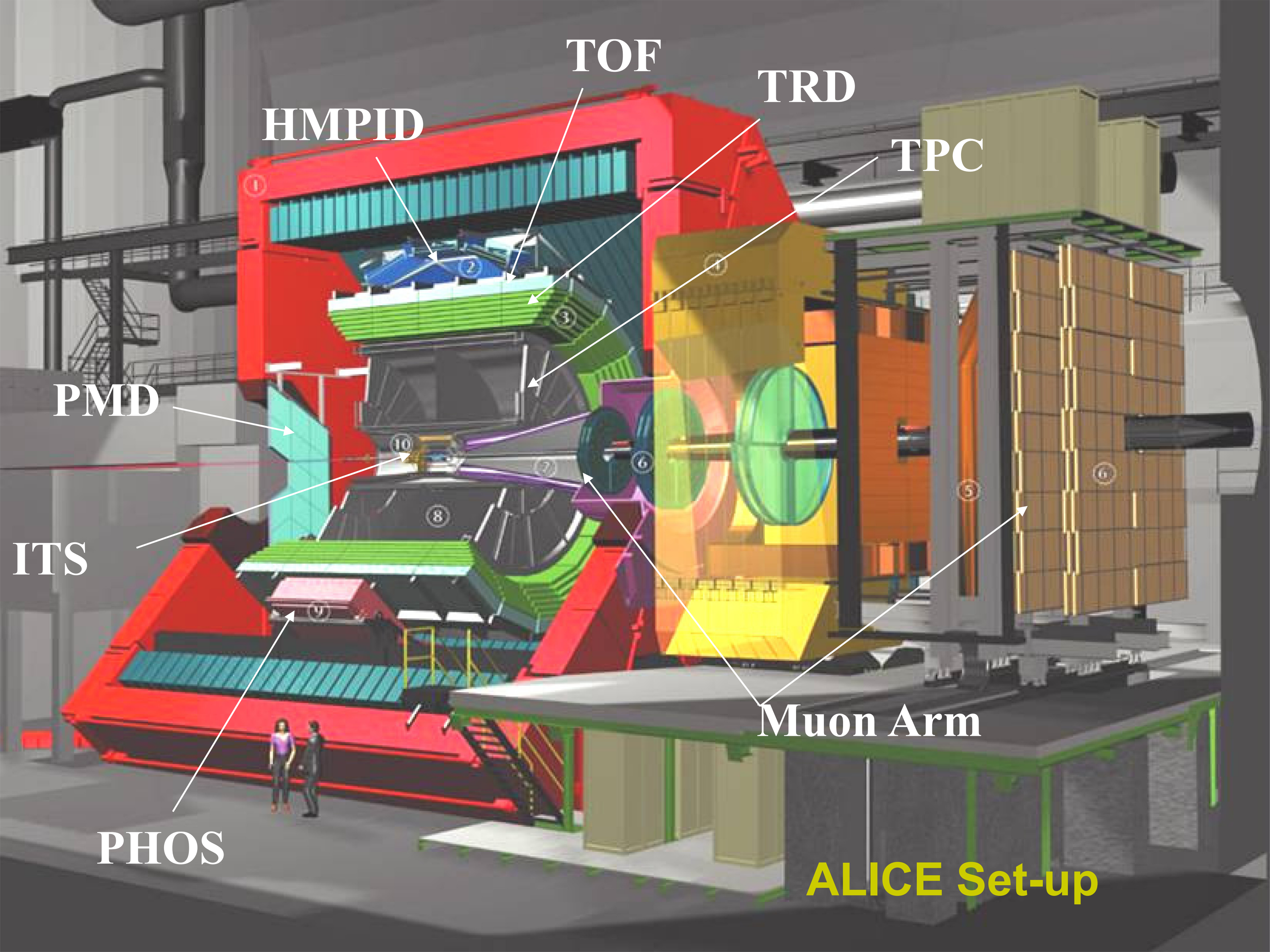


Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

The ATLAS Detector



Diameter	**25 m**	**End-cap end-wall chamber span**	**46 m**
Barrel toroid length	**26 m**	***Overall weight***	***7000 Tons***



ALICE Set-up

Conclusions

- We have taken a random walk through a variety of detector technologies and put the pieces together into a detector

- You can repeat this exercise using the PDG booklet or BRR
  - It contains a wealth of information
  - It is extremely well written and only contains the most essential information

- The design of HEP and HENP detectors is driven by the desire to measure the ID and momentum of all particles in the range from 100 MeV to 100 GeV.
  - all 4 components of the momentum 4-vector (E, p_x, p_y, pz)
  - all 4 components of the spacial 4-vector (ct, x, y, z)

- If you can afford to do this with full 4π coverage, then your detector will end up looking pretty much like all the other big detectors. However, there are big differences in the details and cost effectiveness of each detector design.