Tracking and Particle ID

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Today: Building a tracker

Tomorrow: Reconstructing tracks and identifying particles

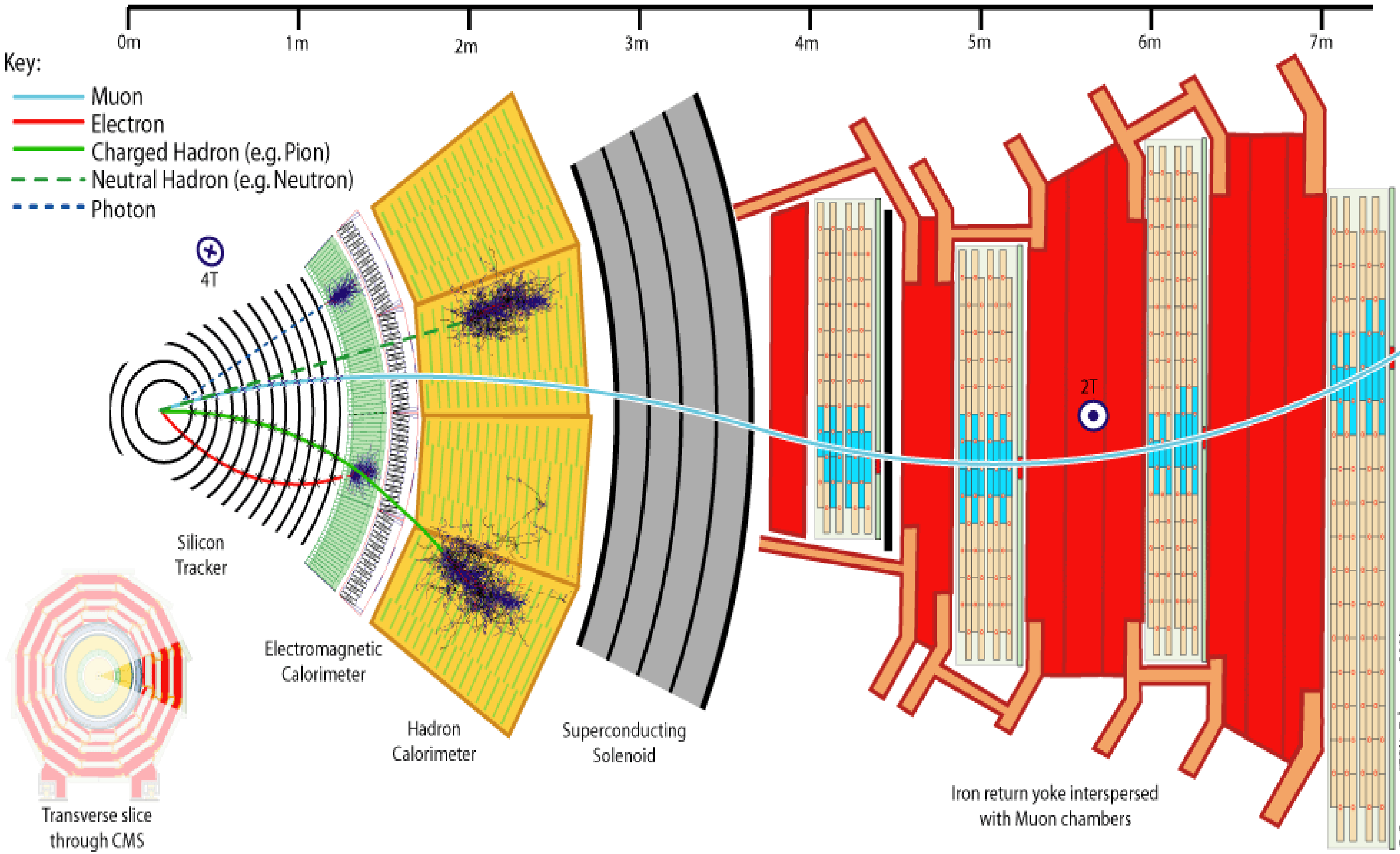
What is tracking and why do we need it?

Tracking is used to reconstruct the trajectories of charged tracks. From these trajectories we can derive a lot of information:

- Measure the momentum of particles (requires a magnetic field).
- Combine with EM calorimetry to distinguish electrons and photons and more accurately measure electrons.
- Combine with muon detectors to accurately measure muons.
- Make vertices to locate the source of the particles.
- Identify tracks and vertices not from the collision (b-tagging).
- Identify tracks from pileup vertices (extra collision vertices).
- Identify photon conversions, K_S, Λ and other strange baryon decays, nuclear interactions, decays-in-flight, etc.

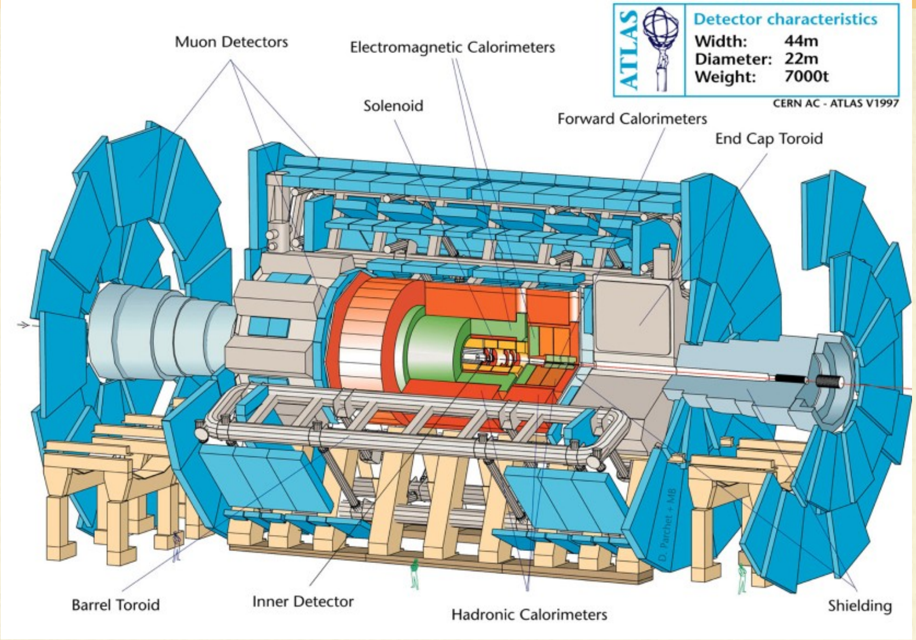
Tracking is needed for pretty much every physics analysis.

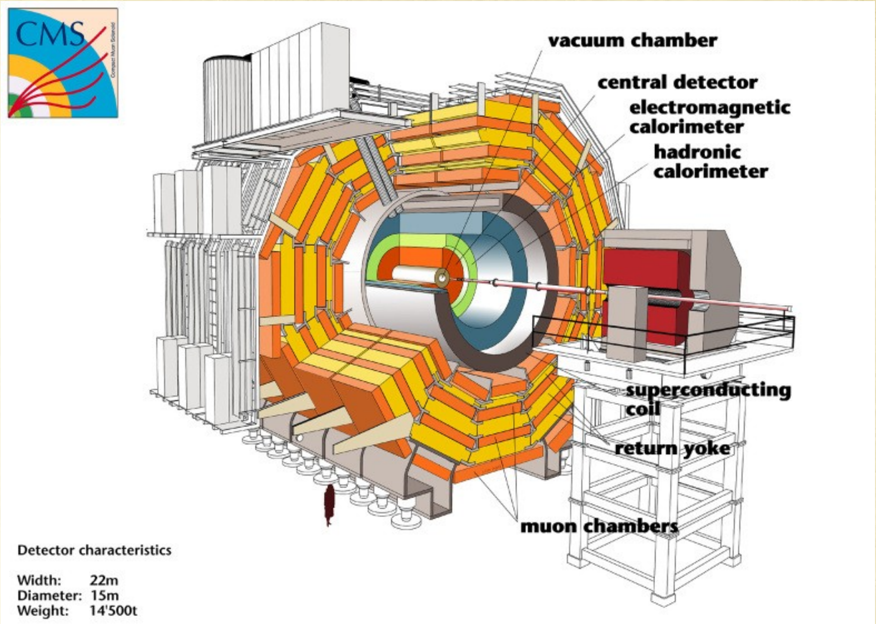
CMS Slice

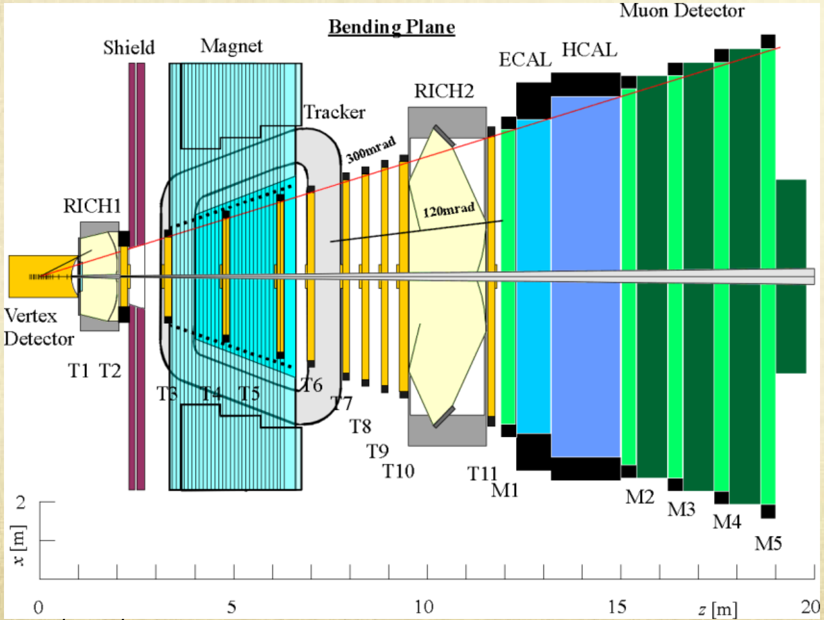


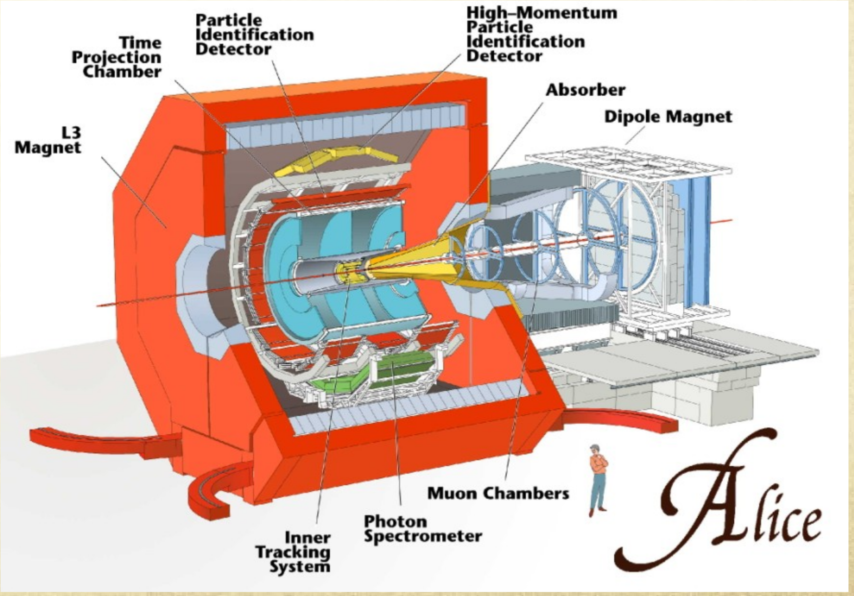
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

All the LHC detectors have tracking









Ionization

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

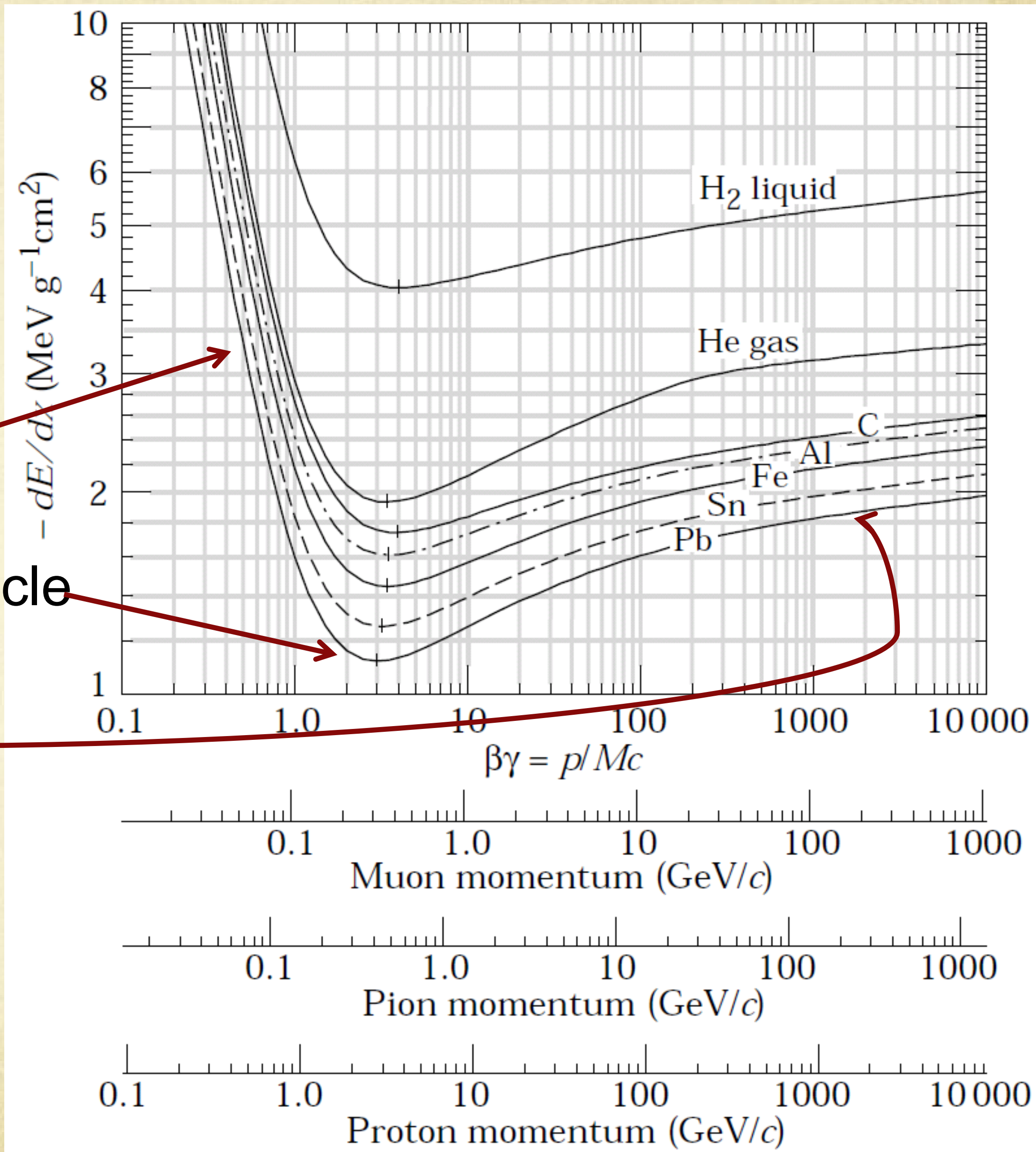
All tracking devices utilize ionization to track particles.

Average energy loss is calculable using the Bethe-Bloch equation

1/β^2 drop is where PID using dE/dx can be done.

MIP: Minimum Ionizing Particle

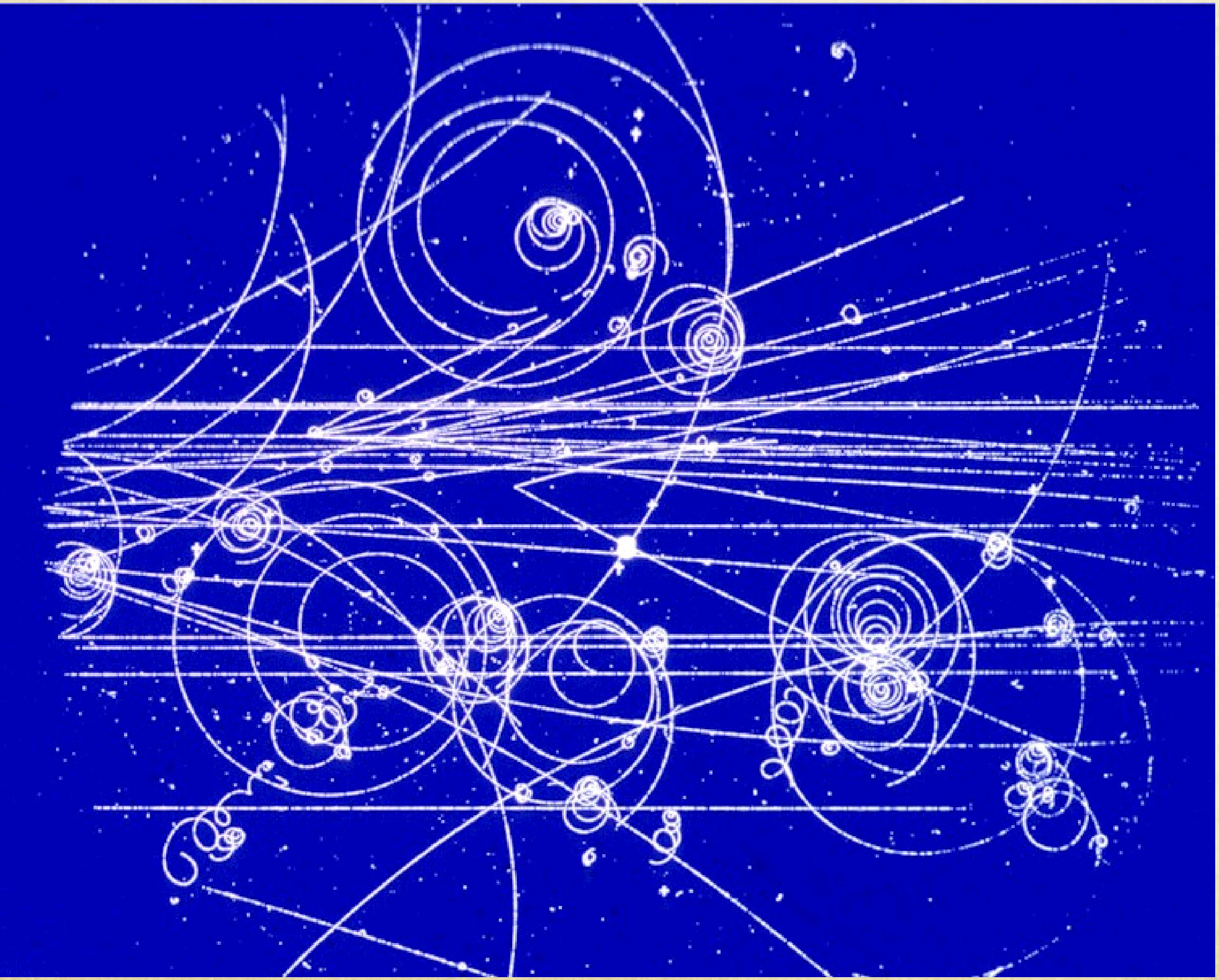
Relativistic rise is a slow rise from the minimum.

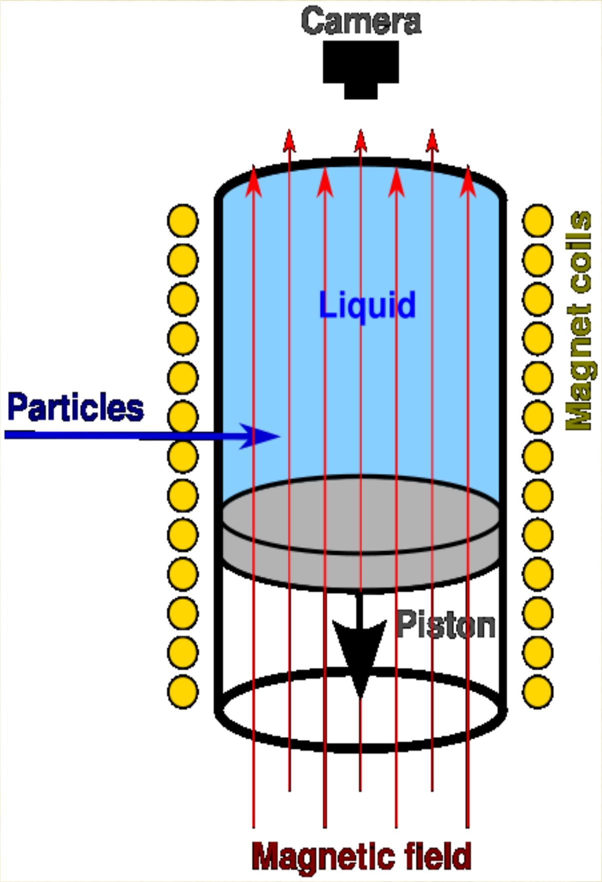


Roughly:
dE/dx = −2 MeV/(g/cm^2)
dE/dx = –2 MeV/cm × ρ(g/cm^3)

Bubble chambers allowed photos of tracks

Ionization by charged particles in superheated liquid hydrogen causes bubble nucleation which is observed by cameras.

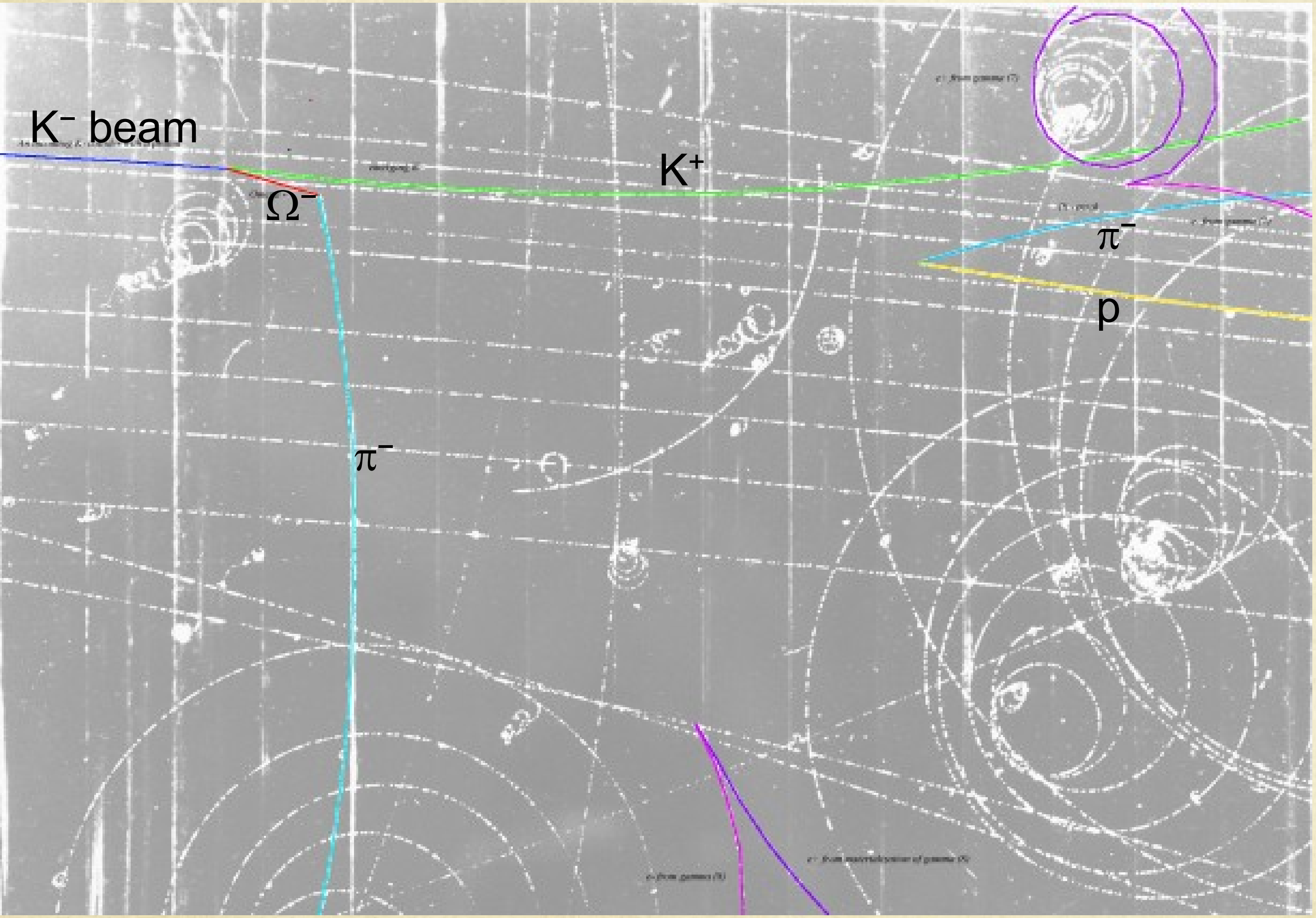




Discovery of Ω^{-} in 1964

$K^{-}p \rightarrow \Omega^{-}K^{+}K_{S}^{0}$ $\quad \Omega^{-} \rightarrow \Xi^{0}\pi^{-}$ $\quad \Xi^{0} \rightarrow \Lambda^{0}\pi^{0}$ $\quad \Lambda^{0} \rightarrow p\pi^{-}$ $\quad \pi^{0} \rightarrow \gamma\gamma$

$\gamma N \rightarrow e^{+}e^{-}$



Bubble chambers do not scale well

Using people to scan events works up to thousands of events but less practical for millions of events.

Also, cycle times restricted the rate to ~10 Hz.

Electronic devices started replacing film in the early 70s.

There are still (low-rate) markets for bubble chambers and emulsion such as WIMP searches (PICASSO and COUPP).

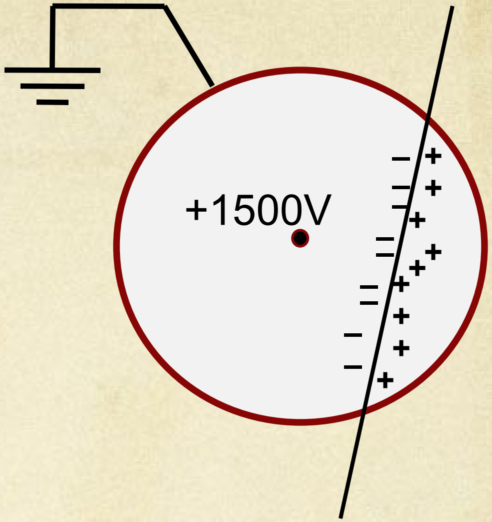
And cloud chambers are fun demos!

Gas Detector (Straw Tube or Proportional Tube)

Particles traverse tube filled with gas and ionize ~100 electrons.

Use an electric field to separate electrons and ions.

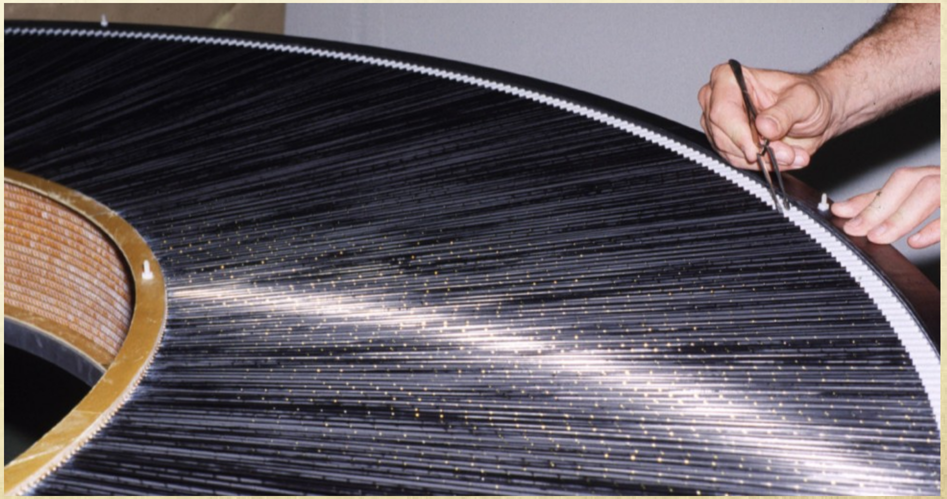
Near anode wire, very high electric field ($E \propto 1/r$) causes electrons to ionize other electrons leading to an *avalanche* providing a gain of ~10^5.



As the electrons have ~constant velocity, can use timing to improve measurement (left/right ambiguity is resolved by multiple offset layers).

Inner wire usually 15-50 μm gold-plated tungsten

Outer shell depends on use: light carbon fiber for inner trackers to sturdy steel for muon detectors.

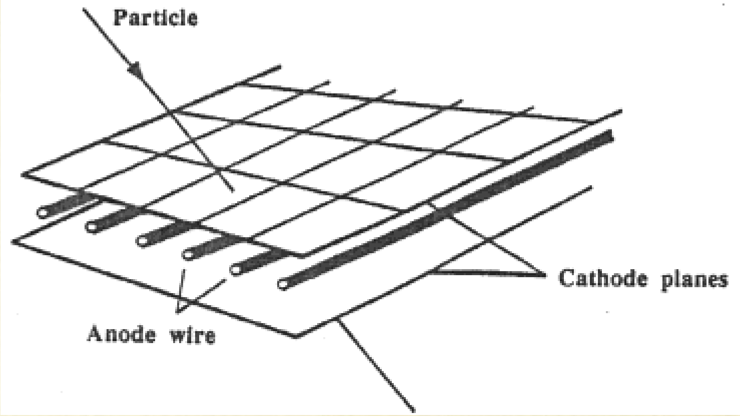


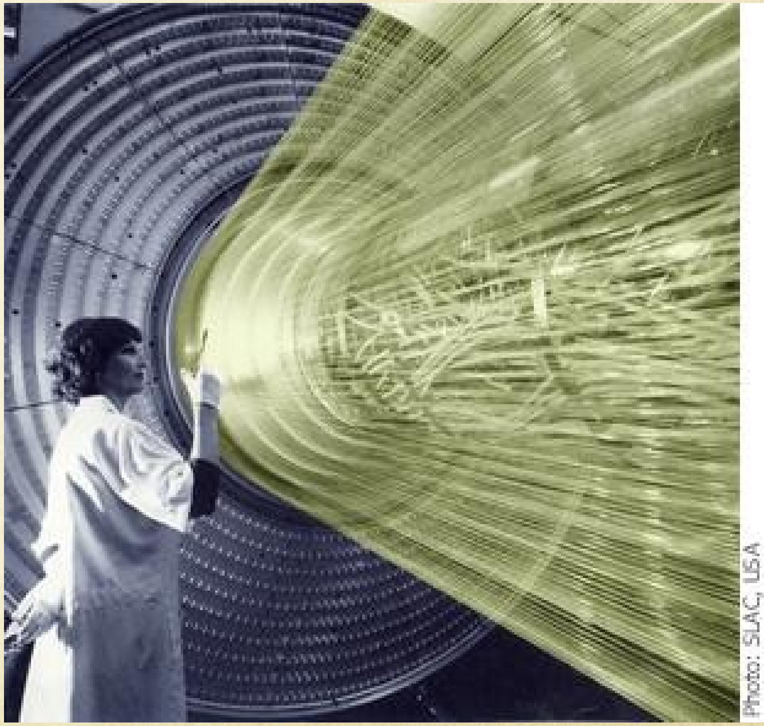
Multiwire Proportional Chambers & Drift Chambers

Can string many wires inside a single gas volume.

If just record presence of signal, call them multiwire proportional chambers.

Can add shaping wires to make electric field more uniform and record the time of the pulse to get distance from sense wires. These are drift chambers.



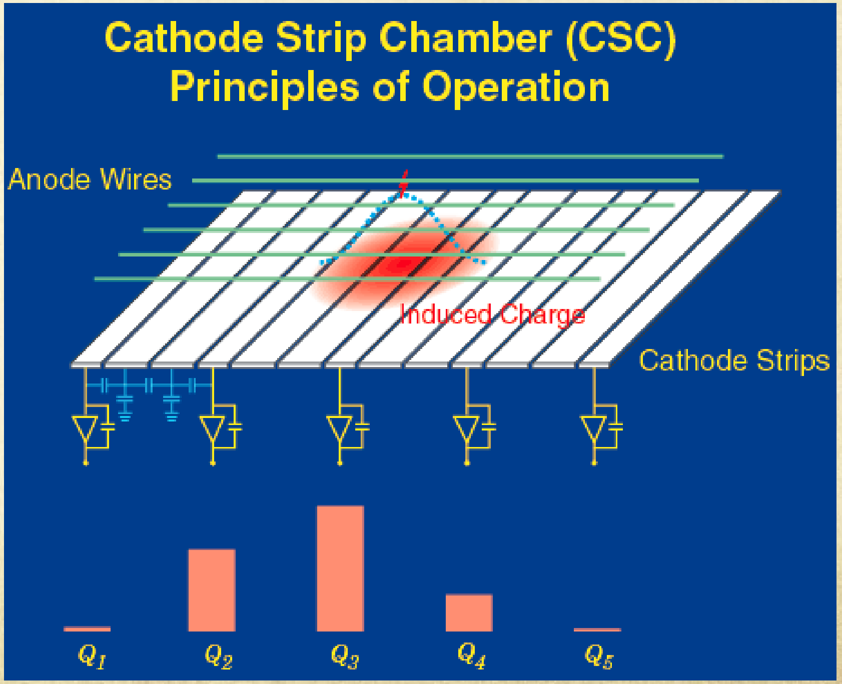


Getting 3D information (stereo views)

In an axial magnetic field (from a solenoid), particles mostly bend in the phi direction so the important measurements are radius and phi (rφ). Wires run along z (no information on z).

Can get z information by making stereo wires at small angle relative to normal wires.

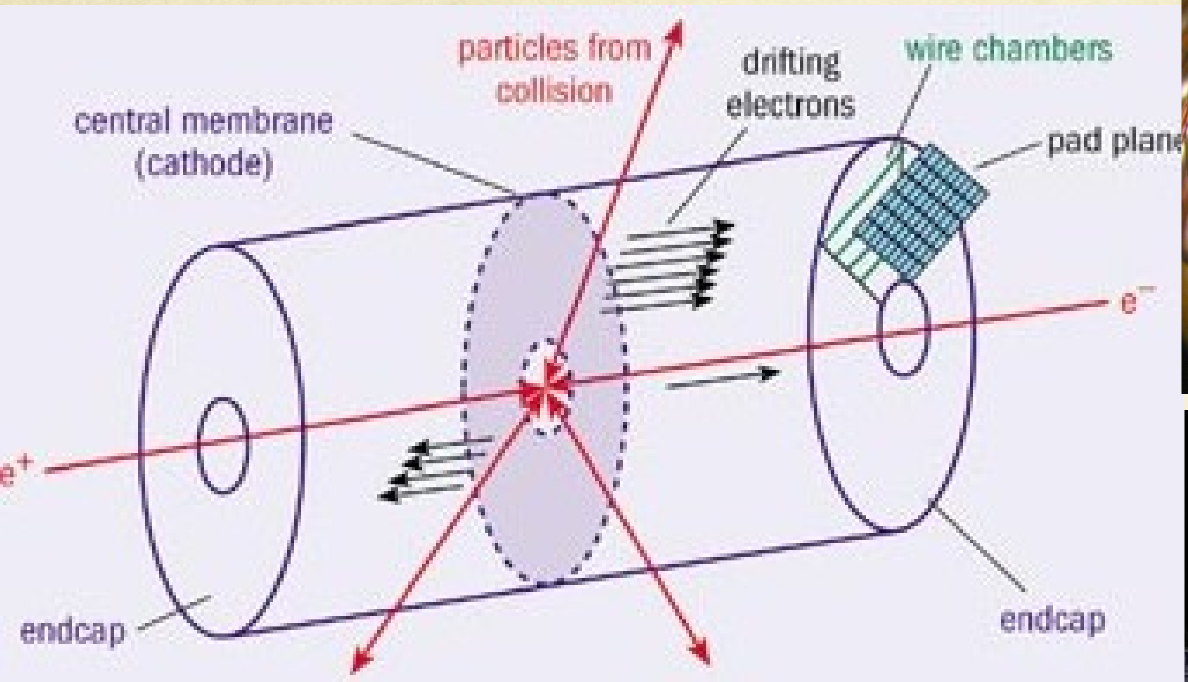
Can also segment the cathode planes (Cathode Strip Chambers, Resistive Plate Chambers, Pad Chambers, etc.)

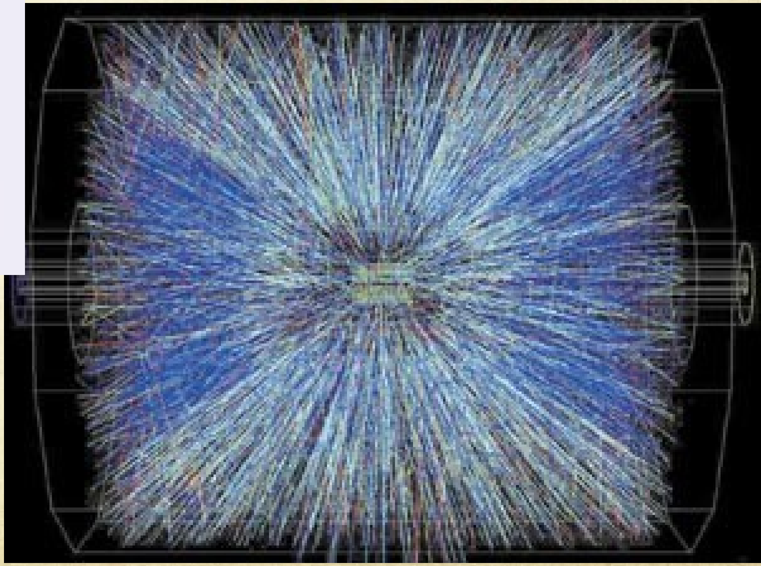


Getting 3D information (TPC)

The Time Projection Chamber (TPC) is a true low mass 3D detector.

Used in ALICE, STAR, ALEPH, DELPHI





The drift time gives z-position and the drift position gives x-y position.

Downside: takes a long time to drift

Silicon based detectors

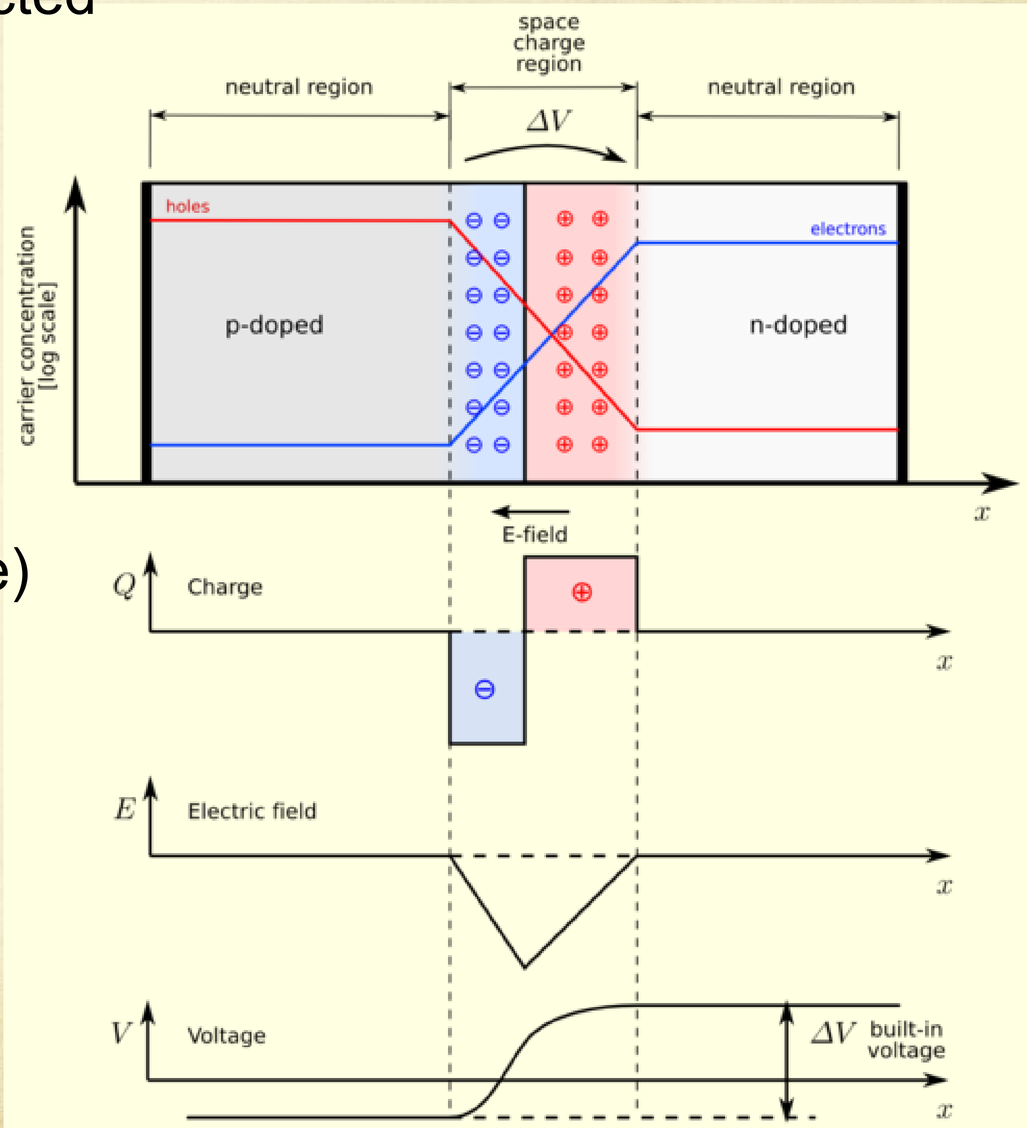
Silicon detectors work under a similar principle: charged particles ionize electrons which are collected

In bulk silicon, electrons and holes recombine immediately.

Solution is a pn junction; similar in operation to a photodiode.

Doping silicon makes excess electron (n-type) or holes (p-type)

Joining p-type and n-type silicon makes a pn junction. Electrons and holes diffuse across junction and combine, making a small "depletion region" with no free charge carriers.



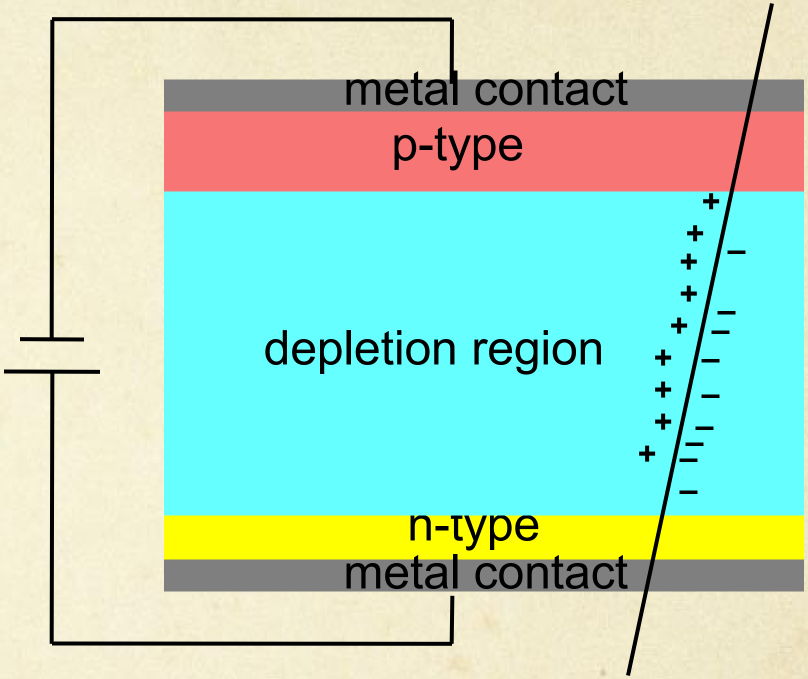
Operating a reverse-biased pn junction

Metal contacts are placed on each side of the junction.

In forward-biased mode, current flows after overcoming 0.7 V potential difference (in silicon).

In reverse-biased mode, increasing voltage causes more electrons and holes to combine, increasing the depletion region.

When the depletion region is as large as the silicon the detector is “fully depleted” and there are (almost) no free carriers (~100V).



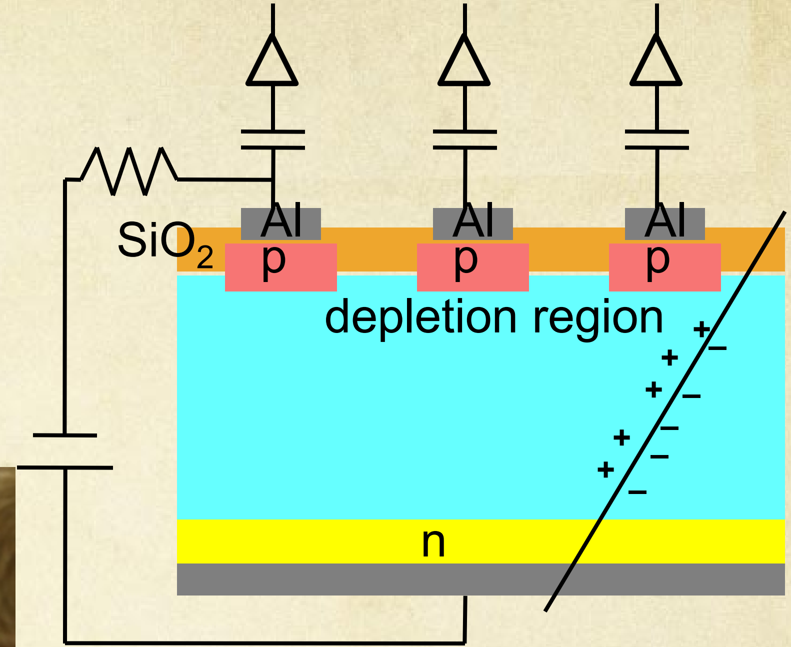
When a charged particle goes through, the current from the liberated electrons/holes can be measured.

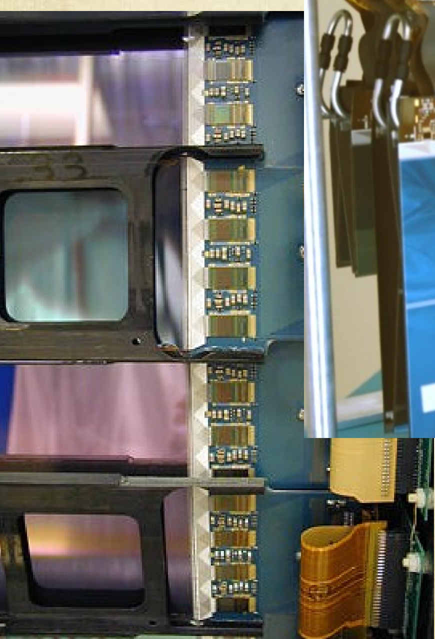
Only ~20,000 electrons-hole pairs from 300μm of silicon so need sensitive current integrating “preamplifiers”.

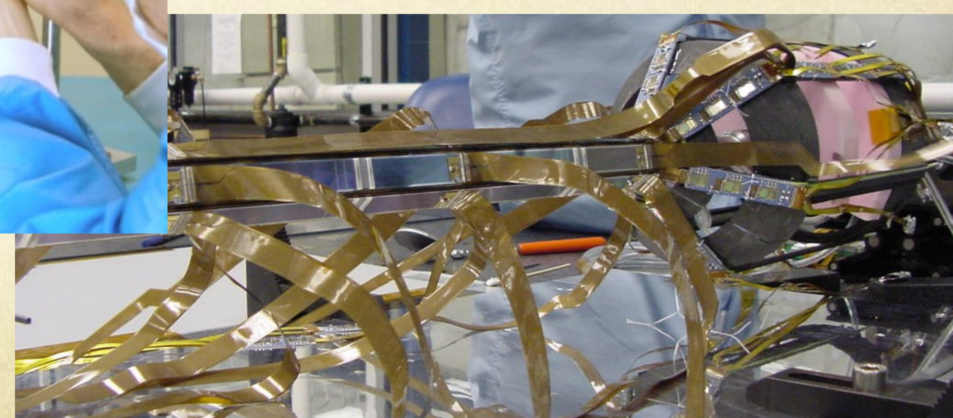
Silicon strip detectors

Need to get signals off the silicon

- Use semiconductor processing techniques to divide into strips with pitch of 25-200 μm.
- Wire bonds and high density flex cables transfer signal off the end.





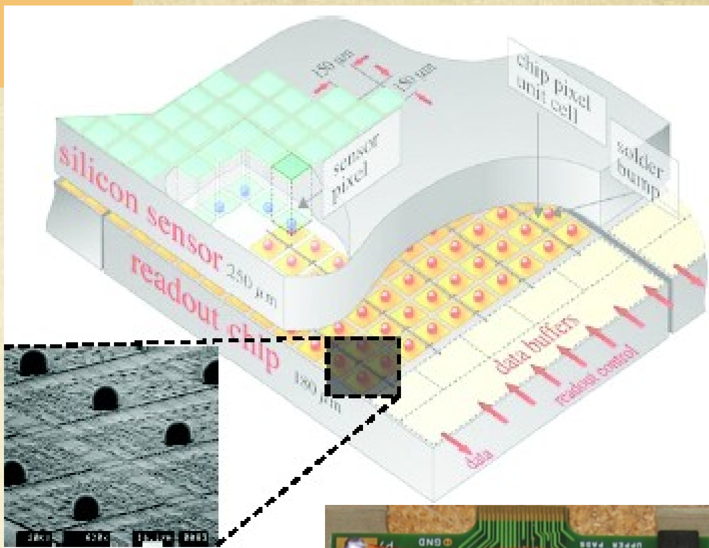


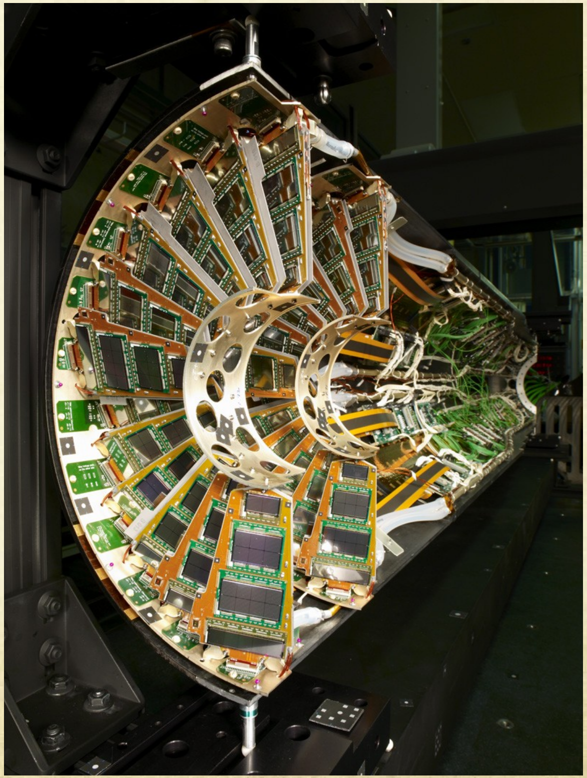
Silicon pixel detector

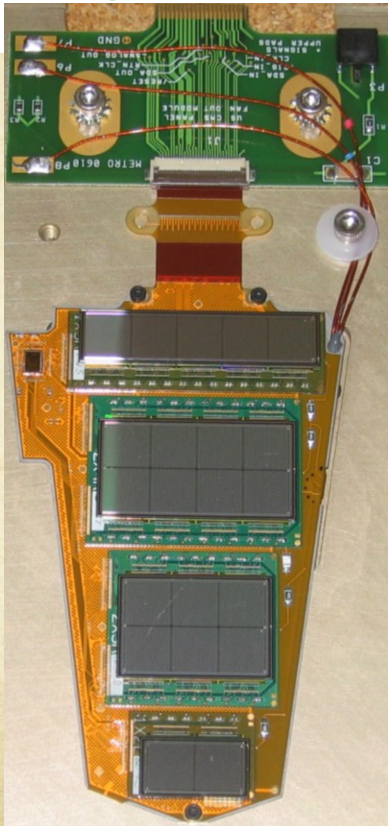
Divide silicon into pixels and mate sensor with electronics readout chip (ROC) using "bump-bonding" to extract signal off the top.

ROC amplifies signals, applies threshold, and ships out hits.

Provides true 3D space point







Hit resolution

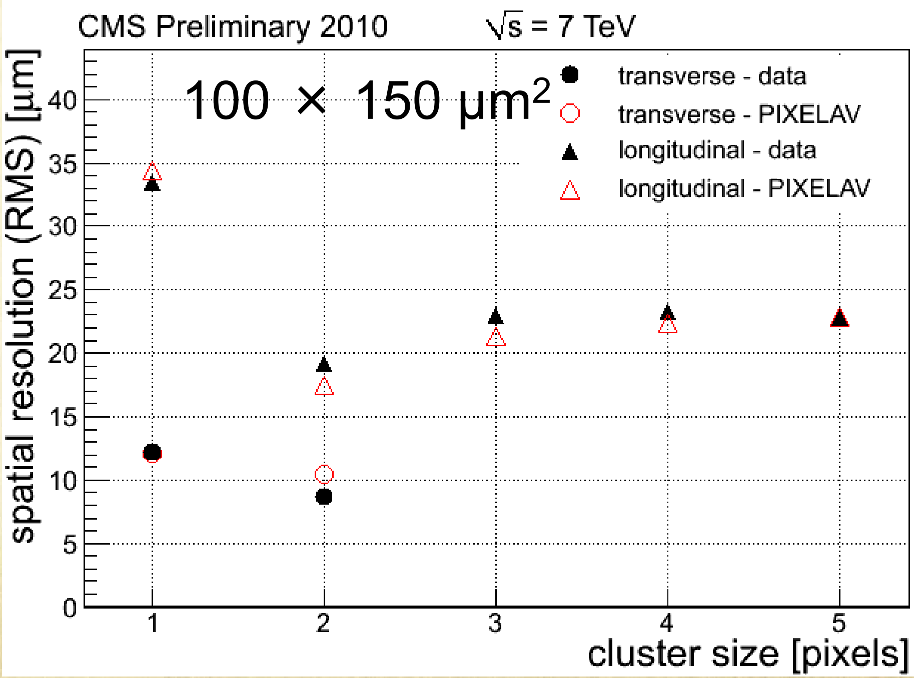
Consider a silicon strip detector with a pitch *p*. If a track leaves a hit in one strip, how well do we know the location of the hit? That is, what is the hit resolution of the detector?

The most sensible location to assume is the center of the strip

Consider an infinite number of tracks spread uniformly across the strip. The standard deviation calculation becomes:

$$\sigma_x = \sqrt{\frac{\int_{-p/2}^{p/2} (x-0)^2 \, dx}{\int_{-p/2}^{p/2} dx}} = \sqrt{\frac{\frac{1}{3}x^3 \Big|_{-p/2}^{p/2}}{x \Big|_{-p/2}^{p/2}}} = \frac{p}{\sqrt{12}}$$

Accounting for charge sharing, can do much better, especially if we record the *amount* of charge deposited in each strip.



How to decide which technology to use?

Remember what a tracker needs to do:

Correctly reconstruct tracks and match them up with calorimeters and muon detectors.

Trackers need to measure transverse momentum well.

Determine interaction vertices and which tracks do not originate from the interaction vertices (b-tagging).

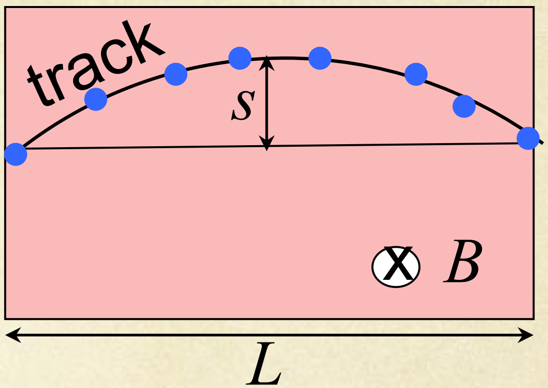
All of this needs to be done for a reasonable cost and in a relatively compact space.

How to measure momentum?

Tracks follow a helix in a uniform magnetic field.

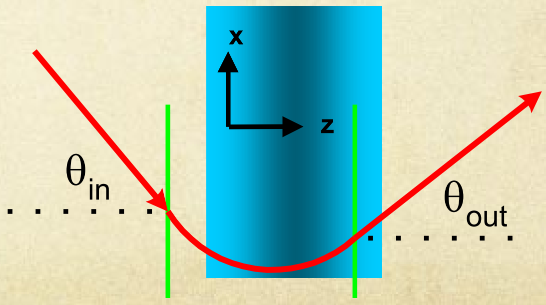
Projected into *rφ* plane you get a circle. With the magnetic field (*B*) and radius (*R*): $p_T\left(\mathrm{GeV}/c\right) = 0.3 \times B\left(T\right) \times R\left(m\right)$

Usually only see tiny part of circle so actually measure sagitta *s* (deviation from a straight line).



Note we only need to measure *rφ* to get the momentum. This is why trackers concentrate on measuring *rφ* and not *z*.

Tracking with a dipole magnet is similar. Usually measure slope into the magnet and slope out of the magnet.



In this case, the important measurement is in the bend plane.

Momentum resolution

With N (N>10) equally spaced measurements, the fractional uncertainty is

$$\frac{\sigma_{meas}(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B \cdot L^2}\sqrt{\frac{720}{N+4}}$$

Worse with increasing p_T (tracks curve less)

Better with increasing B (tracks curve more)

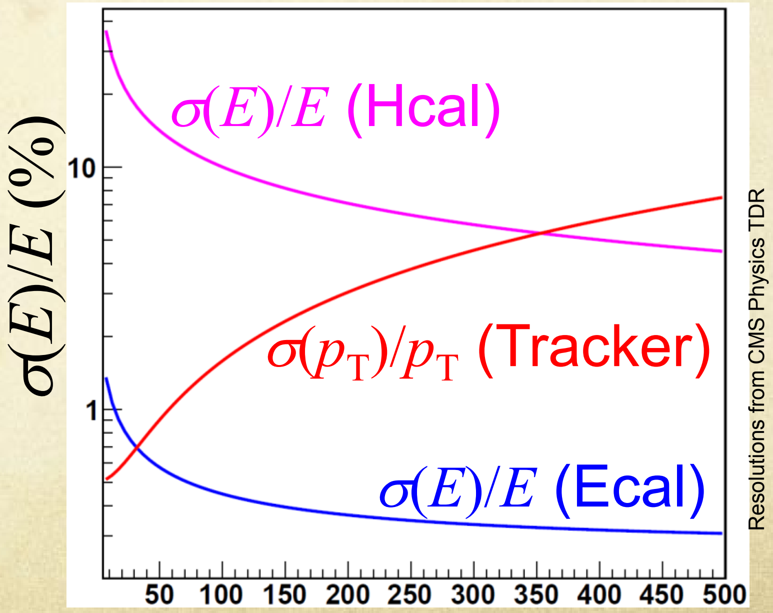
Better with better hit resolution (better measurement of curve)

Better with more √hits (better measurement of curve)

Better with more length^2 (more curve from ∫B·dl × longer lever arm)

For a given tracker, resolution degrades linearly with p_T.

Note that calorimeters behave oppositely – their resolution improves with energy. Complementary.



Resolutions from CMS Physics TDR

Complications in measuring the momentum

The given momentum resolution is OK for a massless detector:

$$\frac{\sigma_{\text{meas}}(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 \cdot B \cdot L^2}\sqrt{\frac{720}{N+4}}$$

What does adding mass do?

Adds multiple Coulomb scattering due to scattering off of nuclei:

$$\frac{\sigma_{\text{MCS}}(p_T)}{p_T} = \frac{28\ \text{MeV}/c}{0.3 \cdot B \cdot L}\sqrt{\frac{L}{X_0}}\frac{p_T}{\beta p}$$

So MCS gets worse as high-Z material is increased (reducing the radiation length X_0) and better with increasing B and L.

For a given detector, MCS is basically constant versus p_T so it is important at low momentum and not so much at high momentum.

Mass (especially high-Z) has other bad effects:

- Energy loss from ionization (and Bremsstrahlung for electrons) – reduces radius of tracks and Brem adds noise to EMCal.
- Photon conversions – reduces photon efficiency and resolution.
- Nuclear interactions – reduces tracking efficiency.

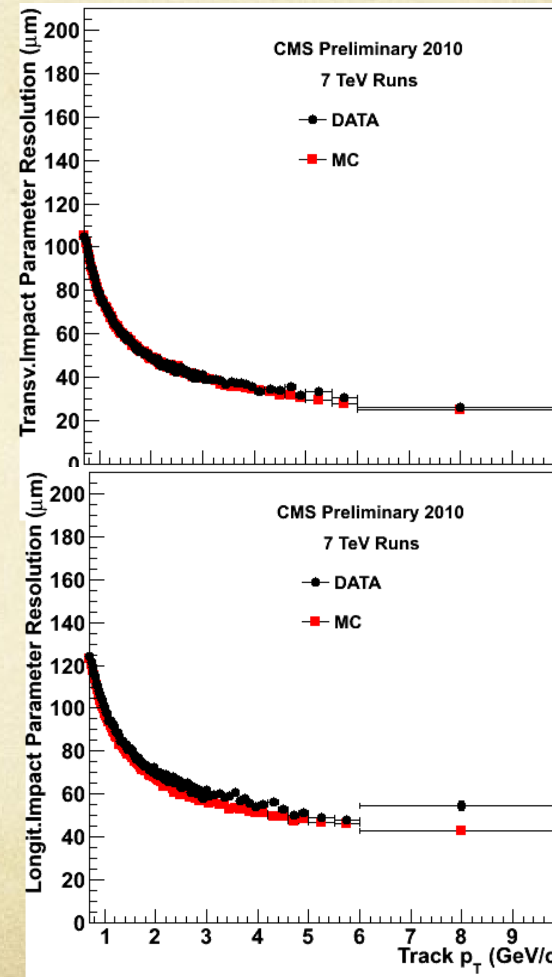
Measuring primary vertices and b-tagging

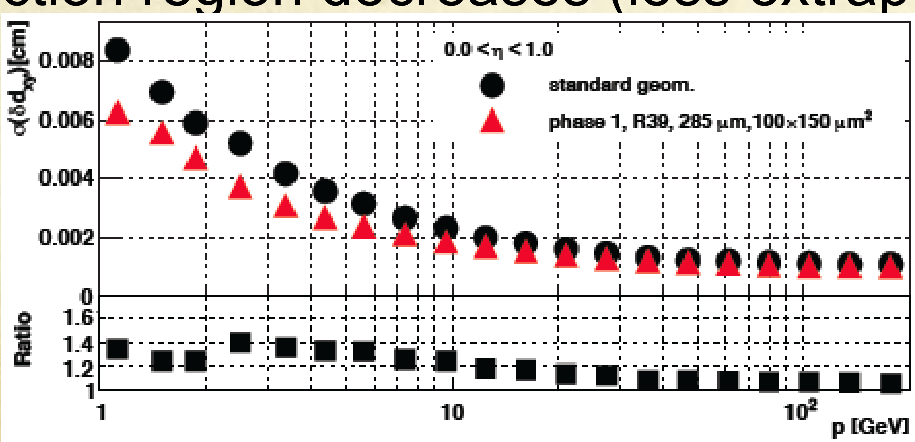
Tracker also needs to be able to do precision vertexing to:

- Distinguish between signal and pileup vertices
- Identify secondary vertices (or at least displaced tracks) to do b-tagging.

The figure-of-merit is the impact parameter resolution which improves as:

- p_T increases (less effect from MCS)
- material is reduced, especially between innermost measurement and interaction region (less MCS)
- distance between innermost measurement and interaction region decreases (less extrapolation)





Some tracker choices

	BaBar	CMS	ATLAS	LHC-b	ALICE
Vertex	3 double-sided strips	3 pixel layers	3 pixel layers	21 strip layers (both x and y)	2 pixel + 2 si drift det
Inner	2 double-sided strips	4 strip layers (2 with stereo)	4 strip layers (4 with stereo)	1 strip layer: 2 x and 2 stereo	2 double-sided strips
Outer	40 layer drift chamber	6 strip layers (2 with stereo)	36 straw tube layers	4 strip/tube layers × 4 planes/layer	TPC
Radius	81 cm	110 cm	105 cm		250 cm
B-field	1.5 T	3.8 T	2 T	$\int B \cdot dl = 4$ Tm	0.5 T
$\sigma(p_T)/p_T$ (%)	$0.3 \cdot p_T$	$.015 \cdot p_T \oplus 0.6$	$.036 \cdot p_T \oplus 1.3$	$.005 \cdot p \oplus 0.3$	

vertex resolution. Small silicon detector for vertex resolution and gas detector for low mass momentum measurement.

LHC experiments at higher momentum (multiple scattering less important) and much higher track multiplicity so more silicon layers (finer segmentation but more material).

ALICE TPC configured for fully reconstructing heavy-ion collisions.

Thoughts on trade offs

Channel count drives cost; the cost of silicon sensors and even strung wire is pretty cheap. The cost comes from electronics.

In silicon, increasing channels leads to increased heat which leads to increased cooling (especially needed to reduce radiation damage). This all results in lots of material – not ideal.

Inner regions in hadron colliders absolutely require finely segmented silicon due to radiation damage and occupancy.

Gas detectors are lower mass, cheaper, and provide more measurement points but have higher occupancy and poorer resolution.

Gas detectors need specific gases and contaminants can ruin a detector. Radiation results in polymerization on wires, reducing effectiveness. In an open chamber, one broken wire can ruin a chamber (straws more robust in this way but have more material).

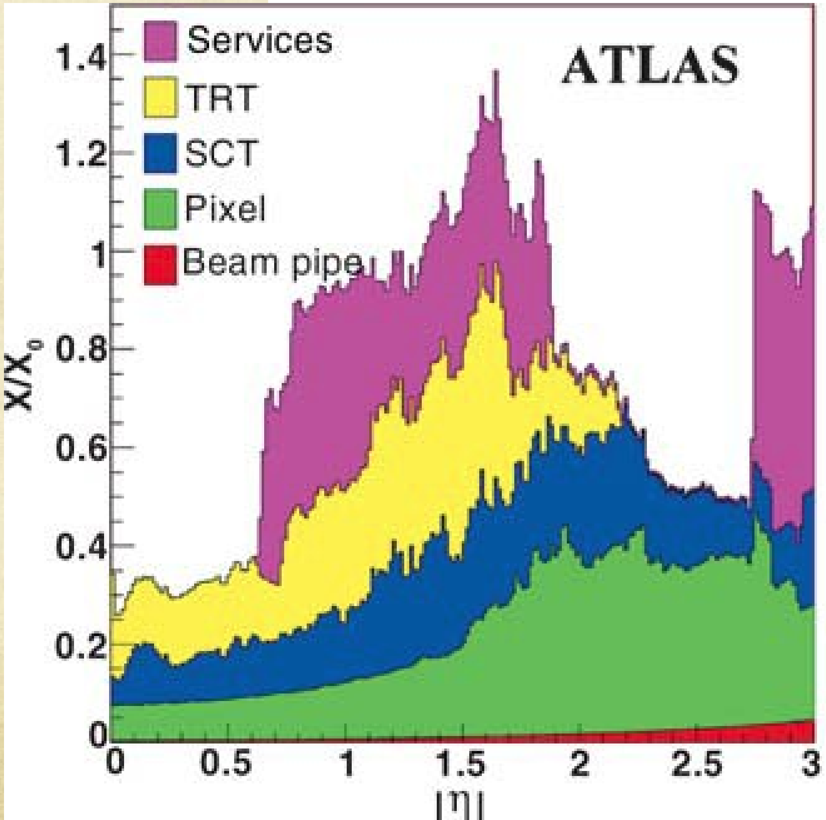
Dealing with material

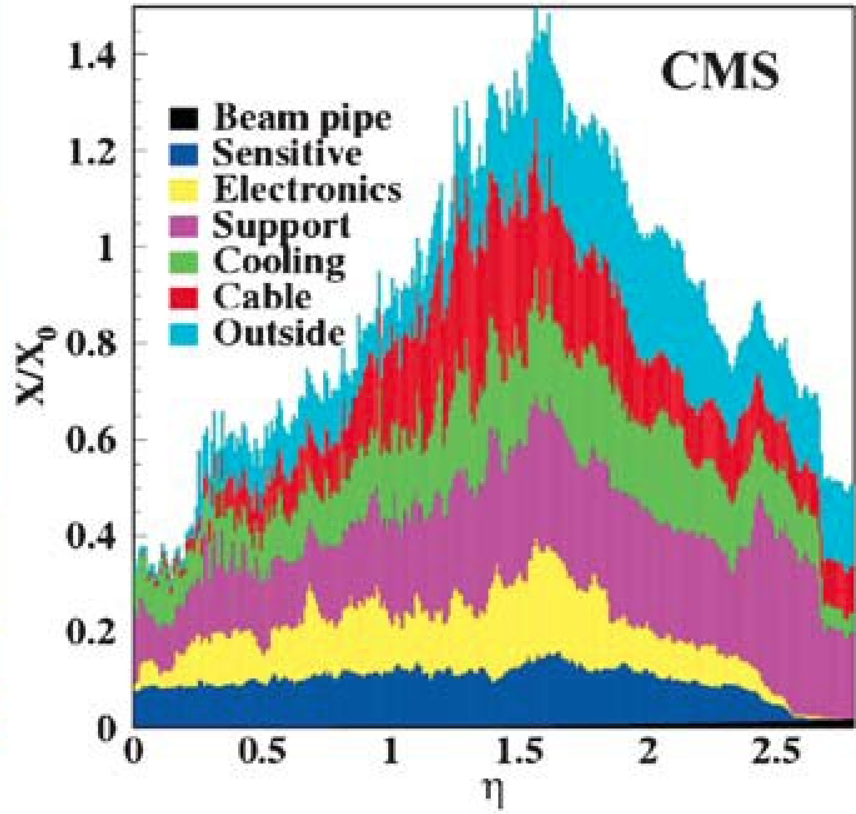
Annu. Rev. Nucl. Part. Sci. 2006.56:375-440.

Keeping the amount of material low is very difficult.

TABLE 5 Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

	ATLAS		CMS	
Date	$\eta \approx 0$	$\eta \approx 1.7$	$\eta \approx 0$	$\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50





Other tracking technologies

There are other, less popular, tracking choices I did not describe:

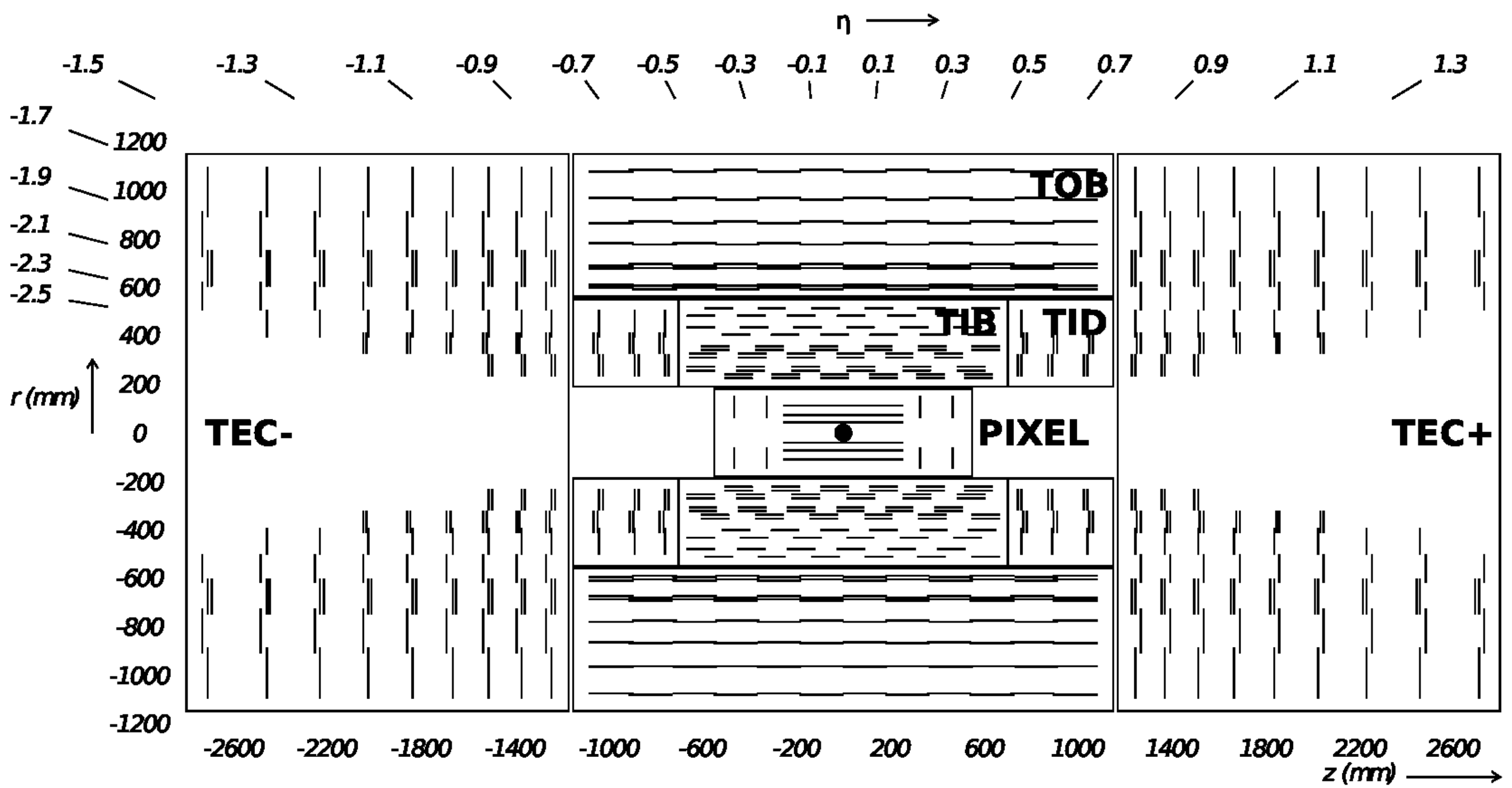
- Gas detectors with special properties: Resistive Plate Chambers (RPC), Cathode Strip Chambers (CSC), Pad Chambers, etc.
- Gas technology on small scales: Micropattern Gas Chamber, Microstrip Gas Chambers, Micromesh Gas Chamber
- Gas ideas in silicon: Silicon Drift Detector
- Emulsion: Tracks recorded directly in film

There is active research into more radiation hard versions of silicon detectors:

- 3D silicon: Instead of collecting just on top, have electrode run in a channel through the bulk silicon.
- Diamond: Make a sensor from undoped diamond.
- Different ways to make silicon to improve radiation hardness.

Backup

CMS Tracker



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