Tracking and Particle ID

June 15-16, 2011

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Yesterday: Building a tracker
Today: Future tech, reconstructing tracks and identifying particles

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
$\sigma(p_T)/p_T$ (%)	$0.3 \cdot p_T$	$.015 \cdot p_T \oplus 0.6$	$.036 \cdot p_T \oplus 1.3$	$.005 \cdot p \oplus 0.3$	
$\sigma_M(\Upsilon \to \mu\mu)$	~75 MeV	67 MeV	119 MeV	52 MeV	

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).

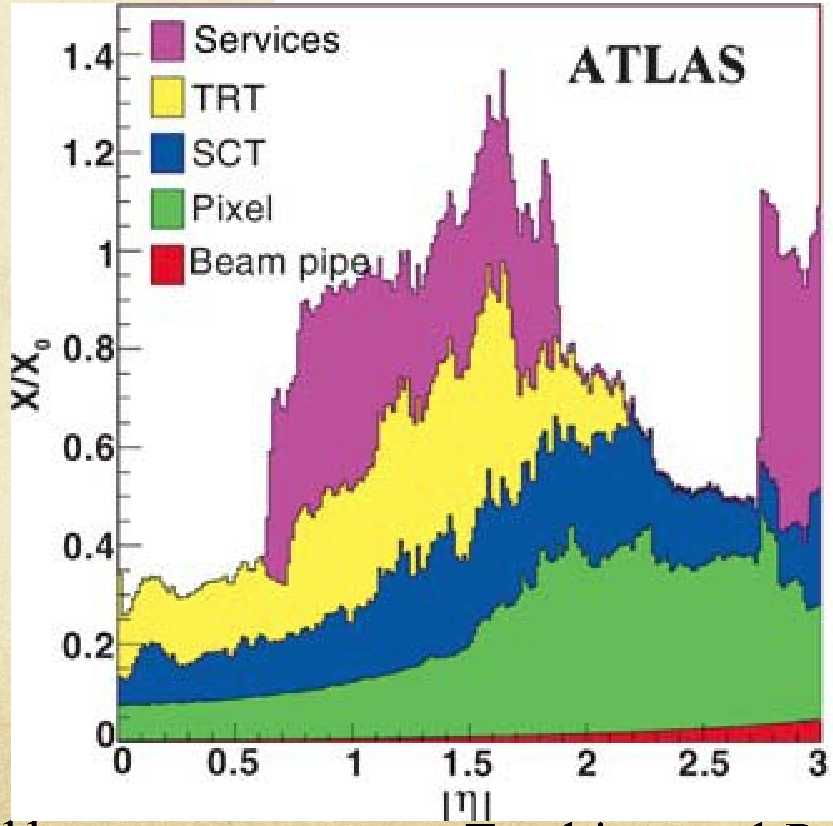
Dealing with material

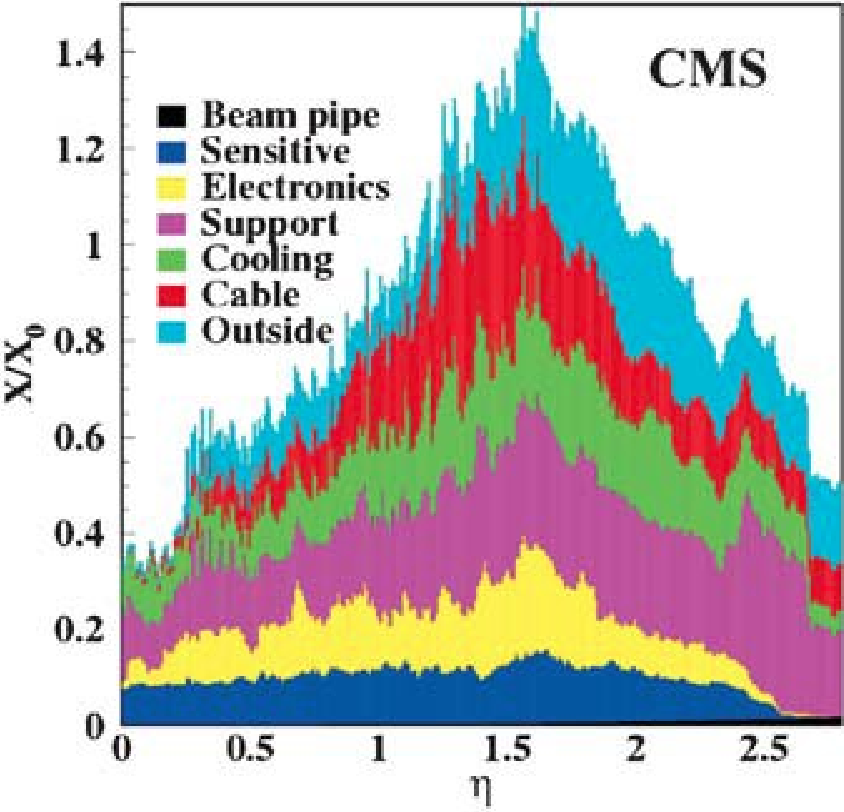
Annu. Rev. Nucl. Part. Sci. 2006.56:375-440.

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

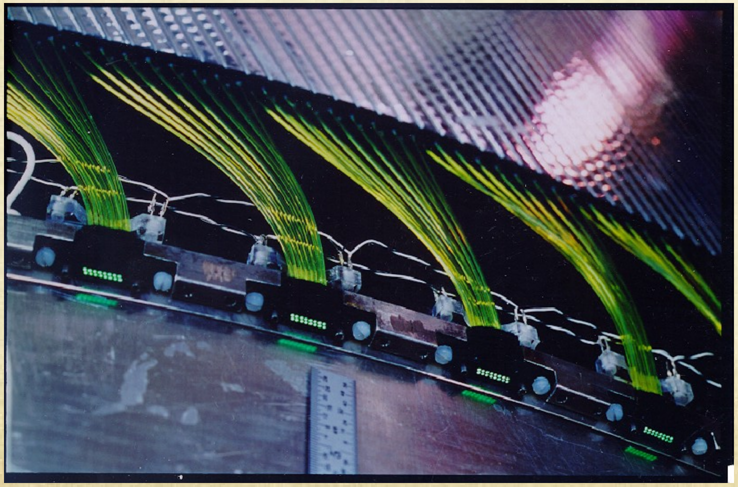


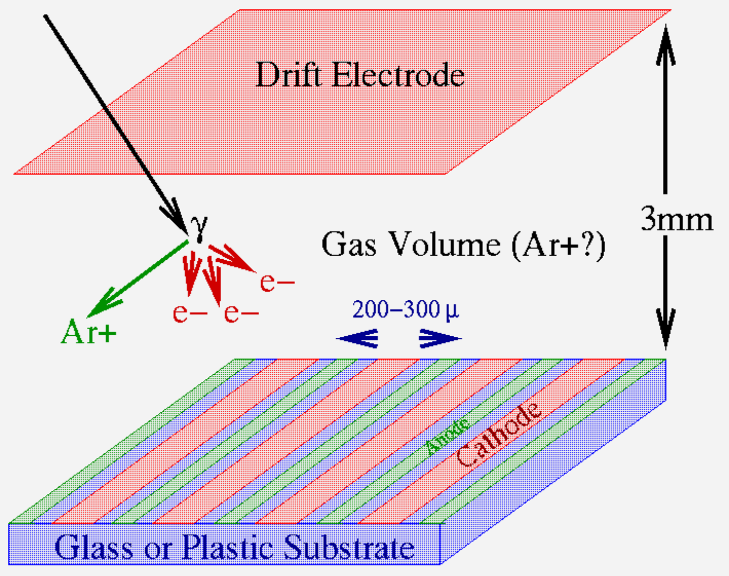


Other tracking technologies

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. (many detectors).
- Gas technology on small scales: Micropattern Gas Chamber, Microstrip Gas Chambers, Micromesh Gas Chamber (HERA-B, HERMES).
- Gas ideas in silicon: Silicon Drift Detector (ALICE)
- Fiber tracker (D0)
- Emulsion: Tracks recorded directly in film





Radiation damage

Most radiation damage is long-term; however there are some short-term effects to be concerned with.

A continual large flux through a wire chamber can cause a “space-charge” effect. The positive ions created when an electron avalanches near a wire are slow to move, causing a reduction in the electric field, reducing the gain for later electrons.

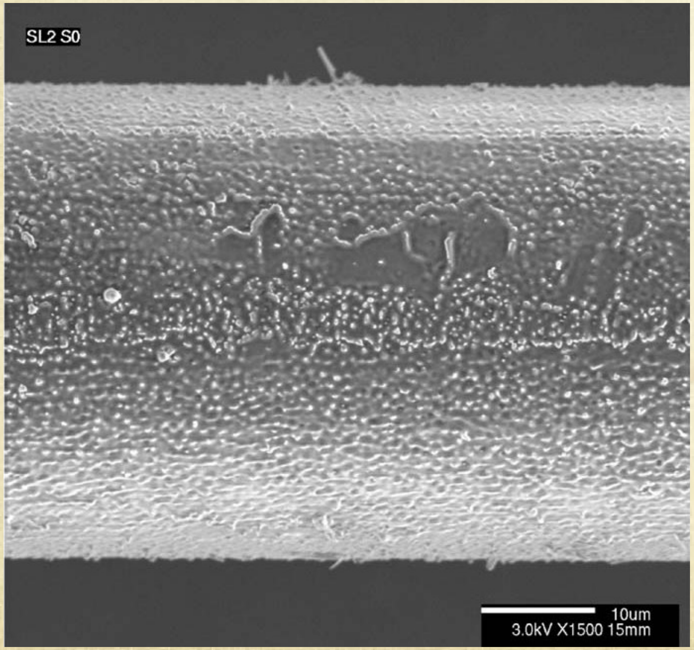
A bad beam scraping event can cause a flood of particles. The resulting power draw can cause problems like burning out an amplifier.

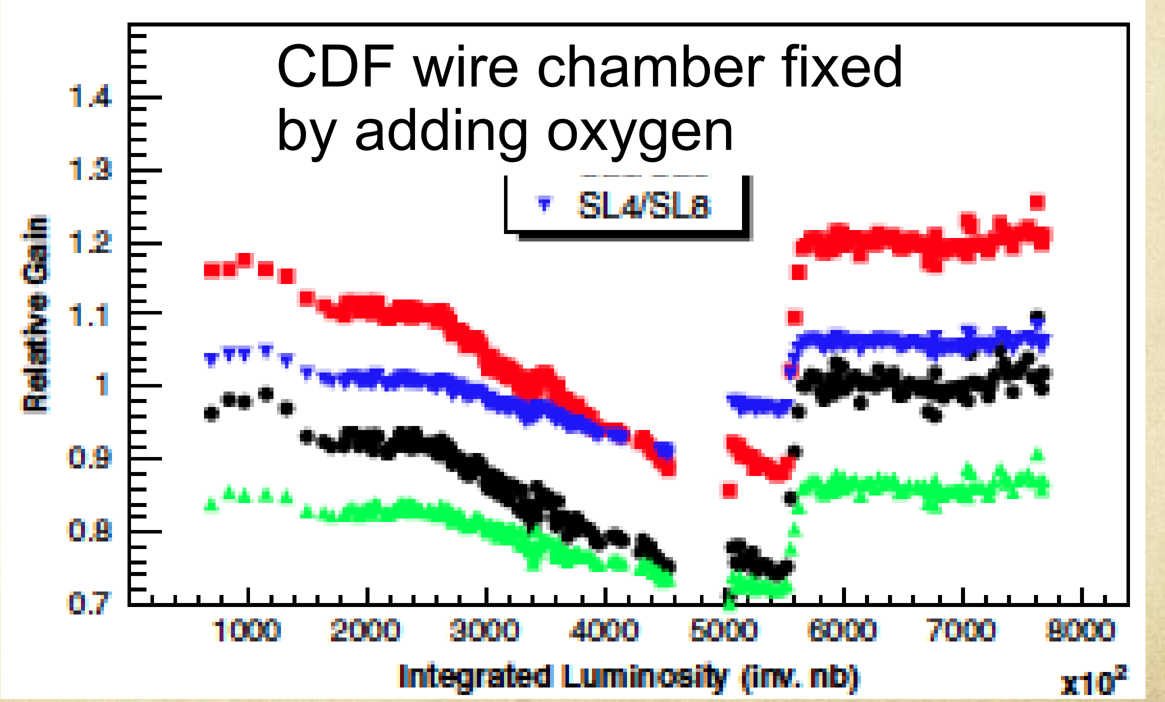
Particles can cause single event upset (SEU) in electronics making them behave improperly. Likelihood scales with particle flux; usually not permanent. Other electronics issues have been resolved through circuit layout knowledge and 0.25μm process.

Long-term radiation damage for gas detectors

For gas detectors it is called aging and is caused by polymerization of wires (gas is flows through so doesn't age):

- During the avalanche, free radicals (like CH_2) can be produced which attach to wire, reducing the electric field and absorbing electrons.
- Can be reduced by using non-reactive gases (nobel gases, CO_2)
- Can often be removed by introducing alcohol or oxygen




CDF wire chamber fixed by adding oxygen

Long-term radiation damage for silicon sensors

Radiation damage generally refers to the long-term effects of integrated radiation dose.

Main effect on silicon is to knock atoms around causing vacancies, interstitials and various other types of defects. The results are::

- Linear increase in leakage current (increases the noise)
- Trapping of electrons/holes (reduces the signal)
- Type inversion of the main silicon (from n-type to p-type) leading to increases in depletion voltage and slower signals.

Modern silicon at the LHC is much more radiation hard than predecessors – oxygenated to reduce effect of radiation, cooled to reduce effect of radiation, and capable of operating with high depletion voltage.

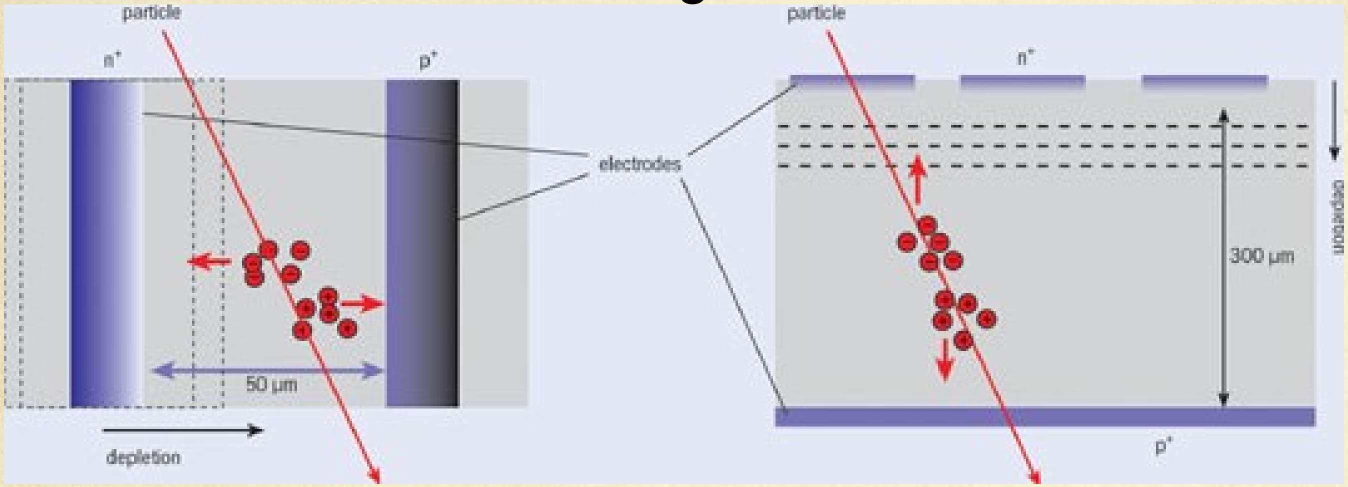
The CDF/D0 silicon was designed for ~6 fb^{-1} while the CMS/ATLAS silicon is designed for >100 fb^{-1}.

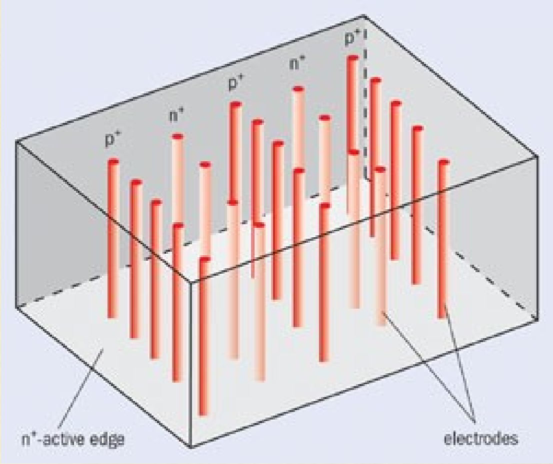
However, the possible luminosity upgrade provides a challenge to current technology. R&D is very active.

Radiation hard research

Improving the silicon sensor (adding more oxygen, using a different crystal structure) – not much gain seen

3D silicon: Instead of electrode only on top, make channels through the silicon bulk.





Try different combinations of p-type and n-type

Try materials other than silicon: silicon-carbide (SiC), gallium-nitride (GaN), and diamond.

How cool would a diamond detector be?

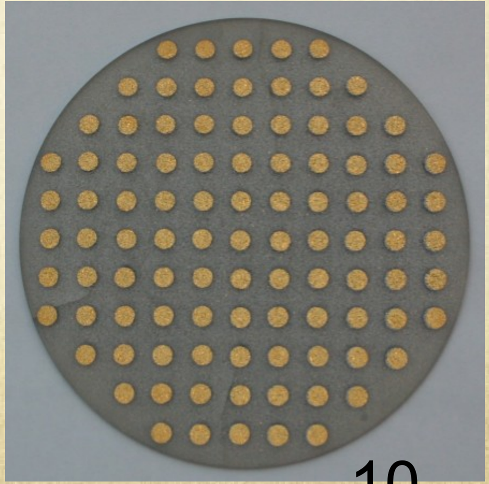
Diamond is a very good insulator.

If you connect electrodes on either side of a diamond and apply an electric field, there is almost no current (similar to reverse-biased pn junction).

However, an electron-hole created inside will flow, giving a signal.

Plasma reactor for growing diamond.

Diamond wafer with 1cm metal pads.



Advantages of diamond (over silicon):

- Radiation hard (lattice won't budge)
- Thermally conductive and doesn't need cooling
- Lower dielectric gives lower capacitance which leads to less noise.
- Very fast (1 ns instead of 10 ns).

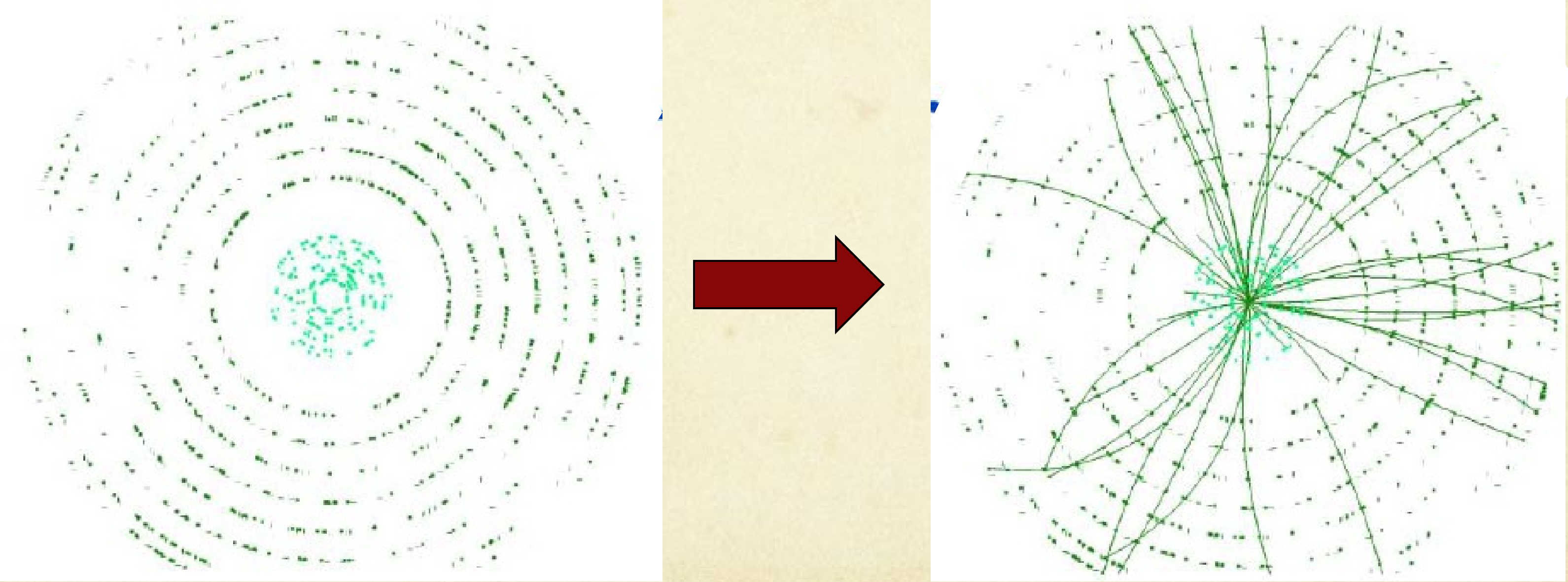
Disadvantages of diamond (to silicon):

- Larger band-gap (signal is ~½ as big)
- It is expensive and very little commercial activity.
- Standard grown diamond (polycrystalline) has poor charge collection.

Reconstructing tracks

Basic steps in track reconstruction:

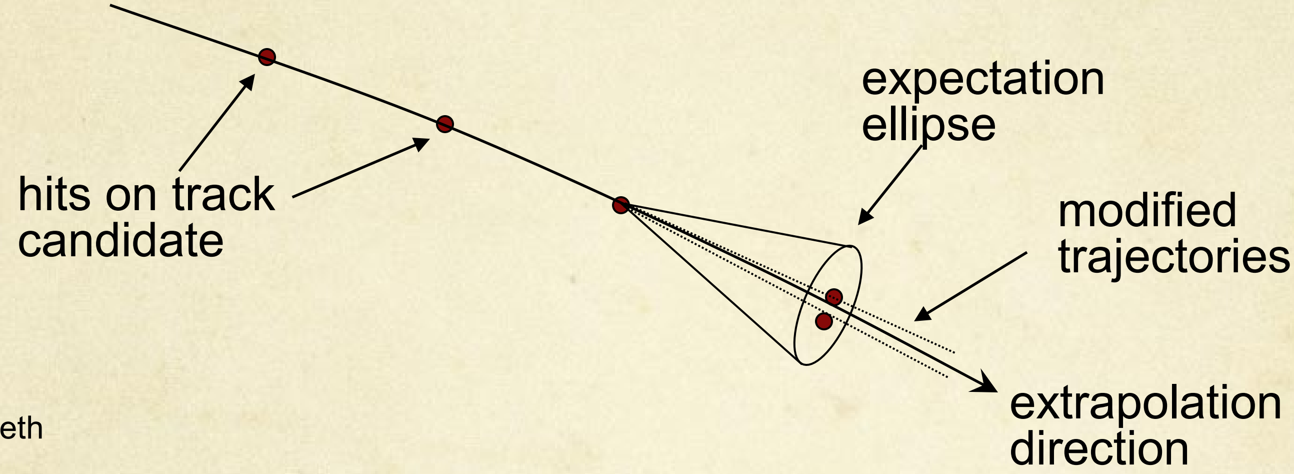
- Pattern recognition: Identifying which hits came from a single charged particle.
- Track fitting: Fitting hits to a single track, taking into account uncertainties, and extracting track parameters.
- Track selection: Applying cuts to remove fake (or ghost) tracks while keeping the tracks of interest.



These steps are often merged to some extent.

Pattern recognition: Sequential hit finding

- Make initial ‘seed’ from two or three hits (can use two hits if no B-field or if constrain to interaction region)
- Project along (and against) seed direction to find additional hits.



M. Hildreth

Seeds can start anywhere in the detector

In the case of a dipole field, one can project in the non-bend view without worrying about the momentum.

There are alternative pattern recognition algorithms (including one which uses a Hough transform) – not covered here.

Track fitting

Simplest fit: take hits (with their associated uncertainty) and perform a least squares fit (χ^2 minimization) allowing the track parameters to vary.

This works fine if the track actually follows a helix.

Multiple scattering and energy loss complicate things because they lead to correlations between the hits and also result in changing track parameters.

The solution developed in the 80s and 90s is the *Kalman filter.*

- Instead of taking all of the hits and fitting them to a function, you start with a trajectory and update, one hit at a time.
- At each hit, a $\Delta\chi^2$ is calculated including the effects of multiple scattering and energy loss as well as the hit uncertainty. Then, the track parameters and uncertainties are updated before propagation to the next hit.
- Gives best track parameters at last point; can fit in the opposite direction (*smoothing*) to obtain best parameters at first point.
- Identical to χ^2 minimization in absence of scattering and energy loss.
- Can be combined with sequential hit finding pattern recognition

Track selection and summary

Not all tracks found will be real and some are more important than others.

Also, tracking is CPU intensive so it may not make sense to spend the time to find every track.

This leads to track selection either early in the process (mostly to reduce CPU) or late in the process (mostly to reduce the fake rate):

Some selection criteria:

- Require the track originate from the interaction region or a primary vertex. Can reduce efficiency for weakly decaying strange hadrons (and maybe charm and beauty hadrons).
- Limit the sharing of hits between tracks
- Limit the number of missing hits allowed
- Require hits be consistent with the track (location, energy deposited, shape of cluster, timing, etc.)
- Require a minimum transverse momentum
- Require a minimum number of hits

What can we do with tracks

- Reconstruct primary and secondary vertices
- Identify b-jets by looking for displaced tracks and/or vertices
- Calculate the invariant mass of fully reconstructed decays
- Perform particle identification using the amount of energy deposited
- Combine with electromagnetic calorimeter, muon system, or Cerenkov system to identify particle type

Making vertices

The first thing done with tracks is to find the primary vertices (locations of the pp collisions).

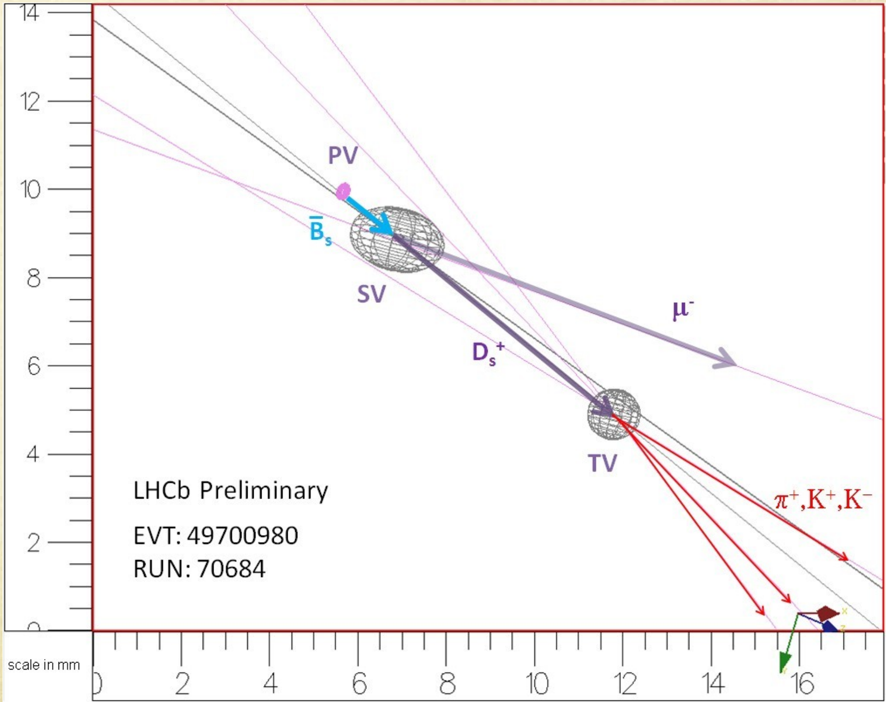
- Not all tracks in an event will come from the same primary vertex

Making primary vertices requires two ingredients: identifying tracks which belong together and fitting those tracks to a common point.

There are many vertex finding and fitting algorithms available, including some which combine the two jobs.

One can also find secondary (or even tertiary) vertices.

One can identify displaced vertices or displaced tracks with jets to provide *b-tagging*.

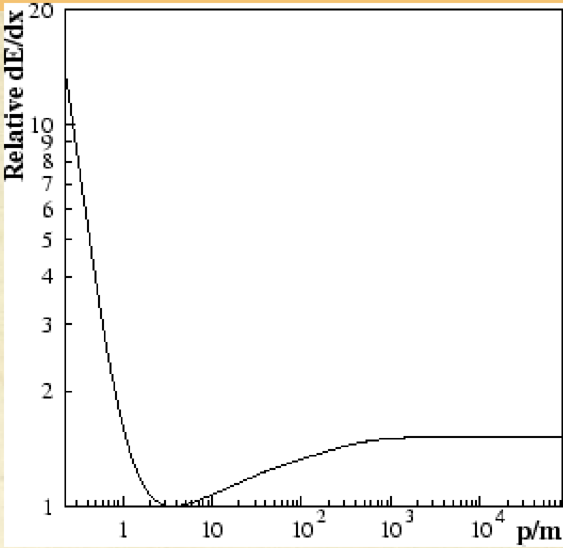


Particle Identification

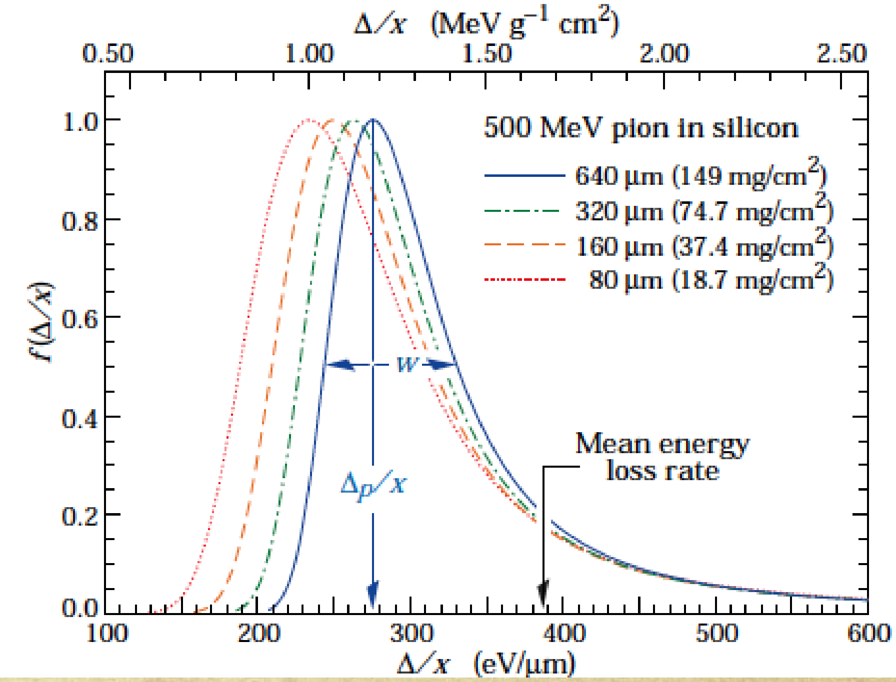
- The long-lived neutral particles are photons, neutrons, and K_L:
  - Photons identified by EM energy with no track
  - Neutrons and K_L can be identified by hadronic energy with no track (very difficult at hadron machines).
- What about identifying charged particles?
  - Since we can measure the momentum, if we can find the velocity, we can obtain the mass. The velocity can be found using:
    - Energy loss (dE/dx) measurement
    - Time of flight (TOF) measurement
    - Cerenkov light
    - Transition radiation
  - Hadrons, electrons, and muons behave differently in material so we can also discriminate with
    - Calorimetry
    - Muon detectors

dE/dx Energy measurement

- As particles pass through matter they lose energy by ionizing atoms.
- The number of collected electrons indicates how much energy was lost by the particle.
- The amount of energy loss is pretty constant for most particles we deal with (p>1 GeV/c).
- At low values of p/m, energy loss changes a lot.

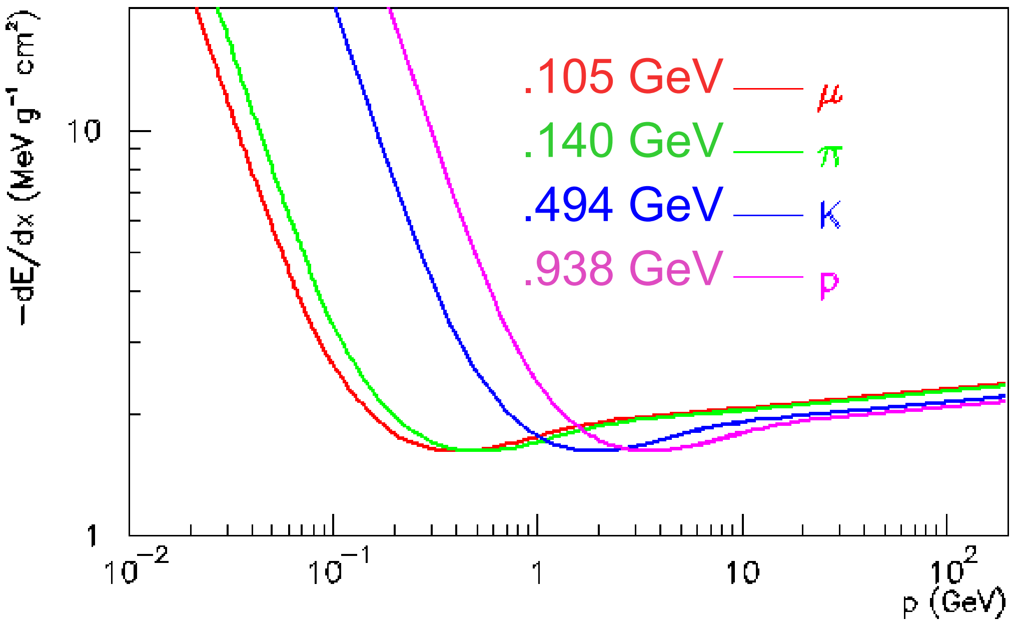


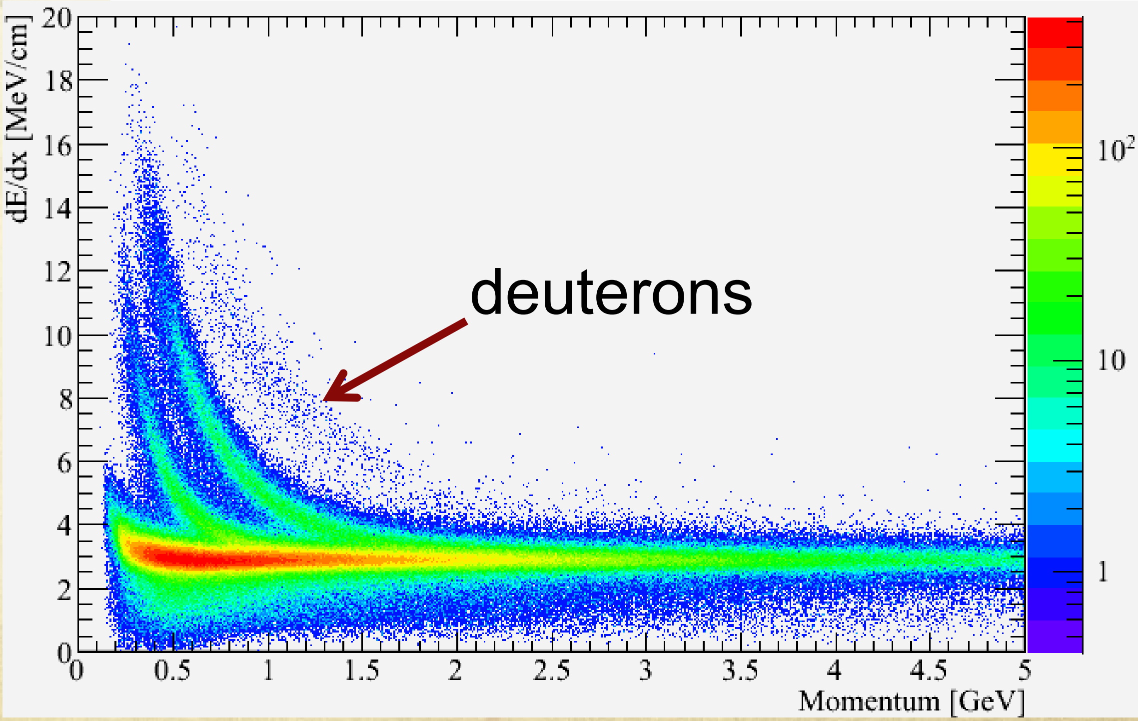
- Measuring energy loss and momentum in this range provides mass
- Note, there are large fluctuations in how much energy is deposited by a given particle in a thin layer.
- Need to average many layers together



dE/dx Measurement

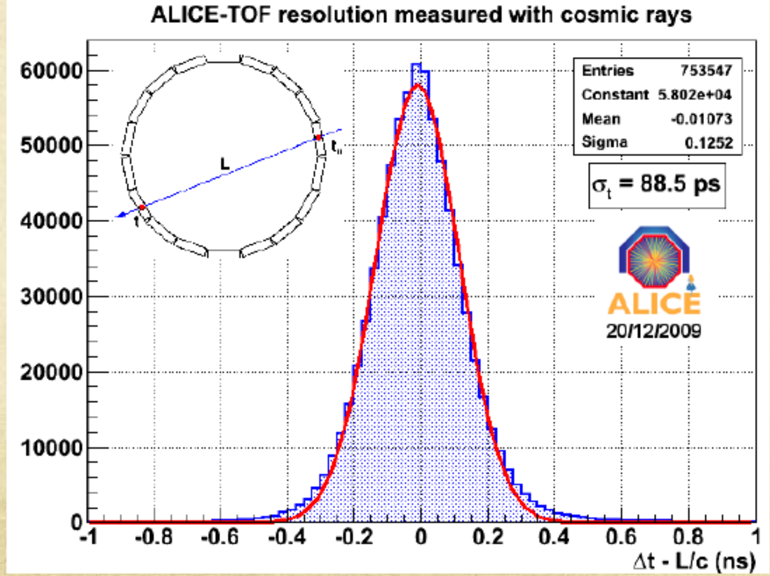
- Plotting the energy loss versus momentum (instead of p/m) shows the differences in particles.
- Can see separation between species at low momentum.

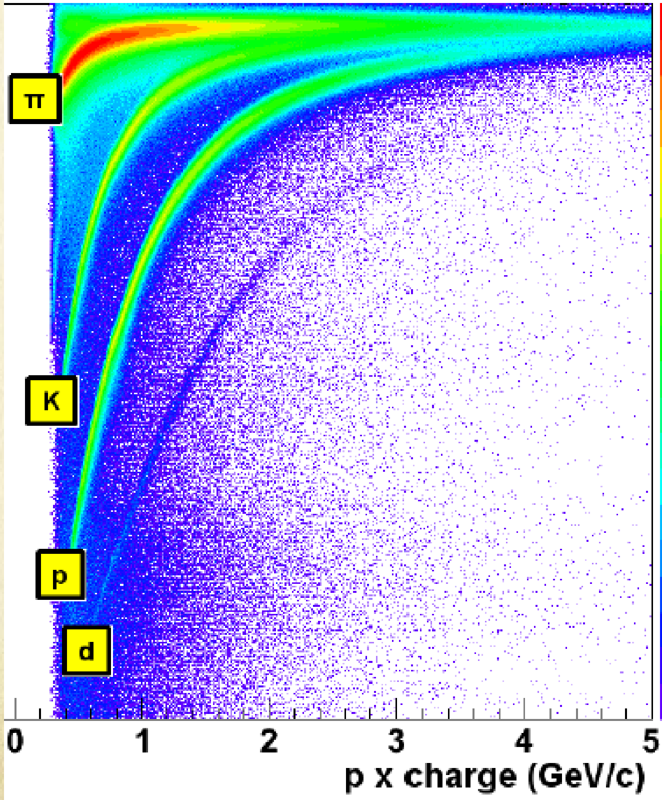



deuterons

Time-of-flight (TOF) detectors

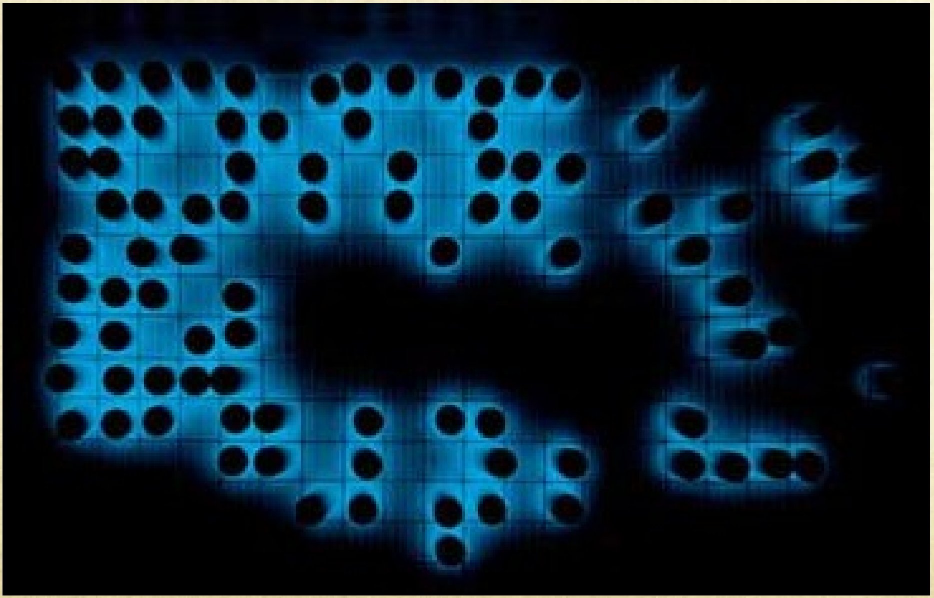
- Another way to determine the mass of particles with low momentum is to use time-of-flight detectors.
- For low momentum particles, β≠1, so for a given momentum, a heavier particle will travel slower.
  - Measure the time to reach a certain point in the detector very accurately (100 ps) to determine velocity and compare with momentum to get mass.
- Usually use scintillator and collect the light.
- ALICE uses multigap RPC's.

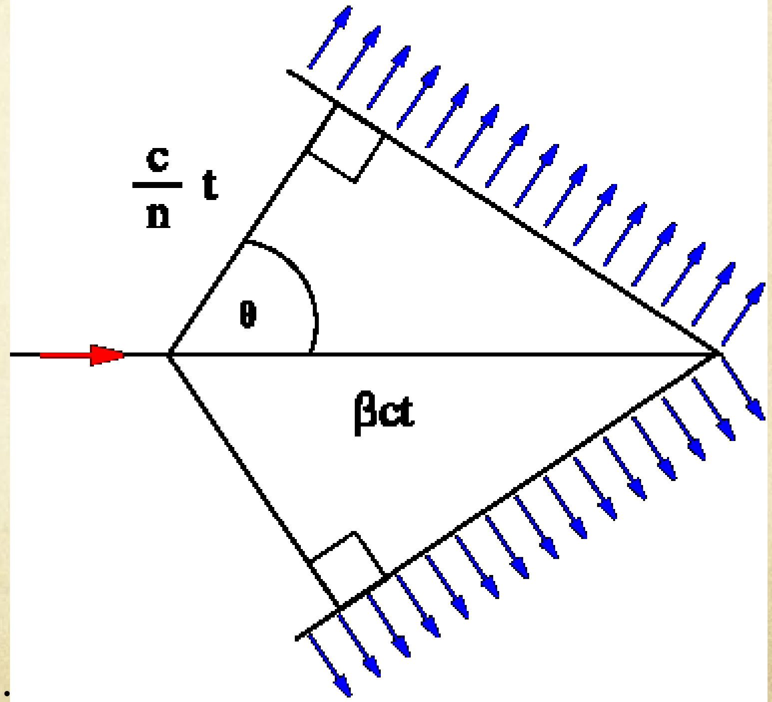




Čerenkov detectors

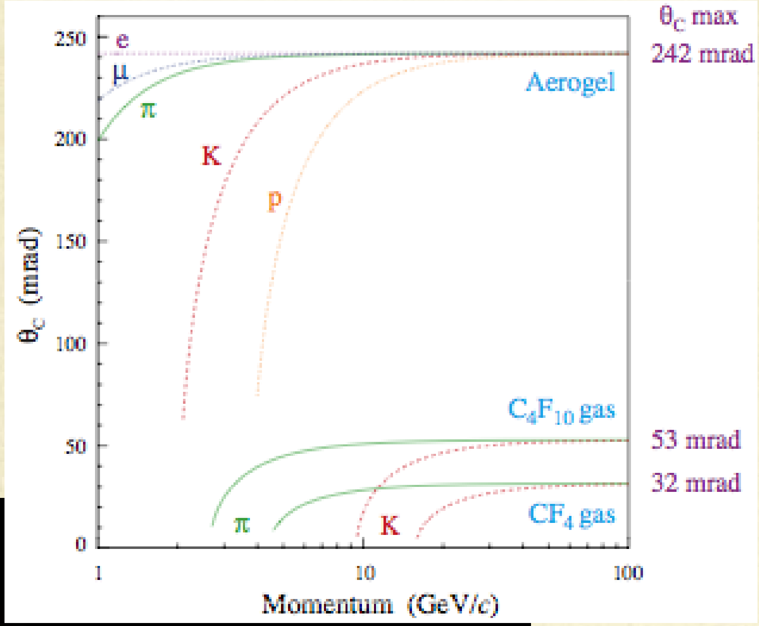
- Another way to determine the mass of a particle by comparing the velocity to the momentum is via the Cerenkov effect.
- When a charged particle travels faster than the speed of light in a medium it emits Cerenkov radiation at an angle which depends on its velocity: $\cos\theta = 1/n\beta$
- Can measure the presence or absence of light to get a limit on the mass (threshold detector)
- Measurement of the angle gives the velocity and combined with the momentum gives the mass.



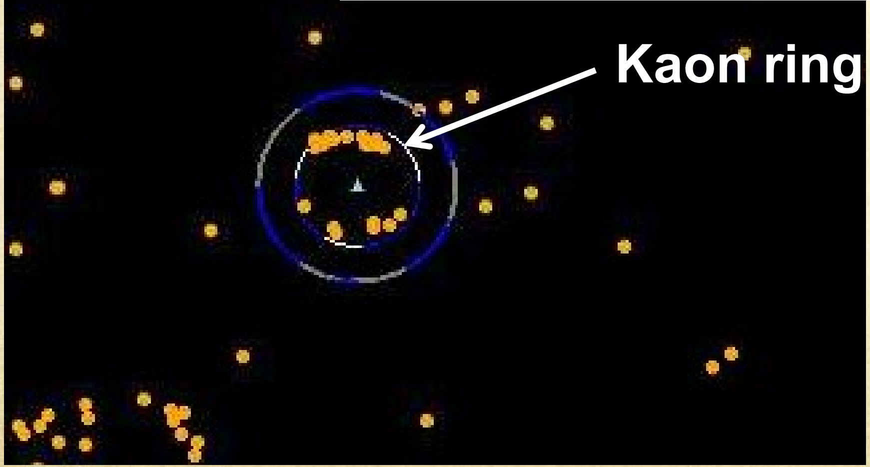


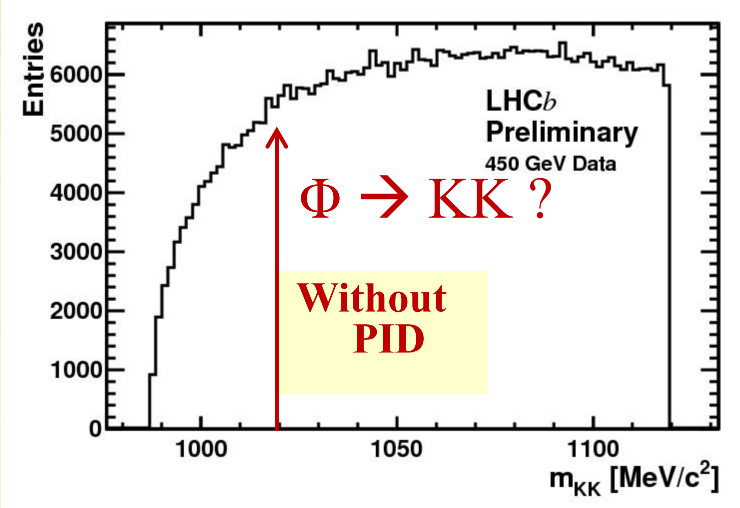
Ring Imaging Cerenkov Detector (RICH)

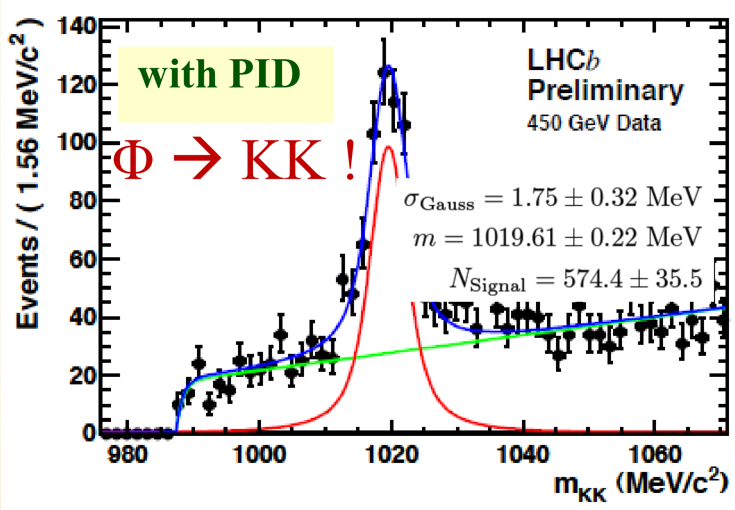
LHCb uses two RICH detectors filled with two different gases plus aerogel in front of one detector (for low momentum tracks).



LHCb data (preliminary)



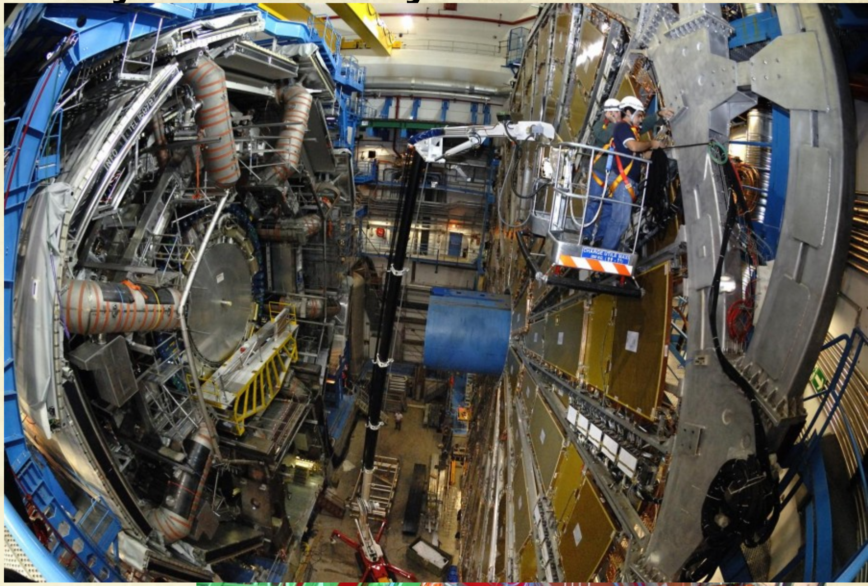


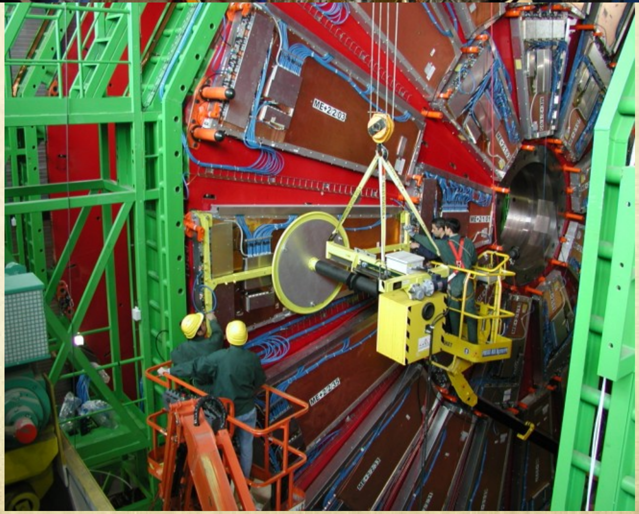


Identifying electrons and muons

Compared to identifying hadrons, identifying electrons and muons is easy because they behave very differently from hadrons and each other.

- Charged tracks which deposit their energy in the EM calorimeter are electrons. Can also use Cerenkov radiation or transition radiation to identify.
- Muons interact less than all other charged particles so place detectors behind lots of material (calorimeters and steel shielding usually) and whatever comes through is a muon.
- Add magnetic field & tracking to find momentum and link with main tracker





Summary

The challenges faced by trackers at hadron colliders are significant. They need to handle the high track density, rate, and radiation while remaining as thin as possible (and affordable).

- Silicon detectors are essential in the inner tracking region (due to radiation and occupancy).
- Gas devices dominate the muon detectors due to the large area that must be covered.
- Upgrades are concentrating on improving radiation hardness and redundancy while reducing material.

I did not discuss the details about using trackers such as calibration of signals, measurement of material and magnetic field, alignment of detectors, measurements of efficiency and resolution, etc.

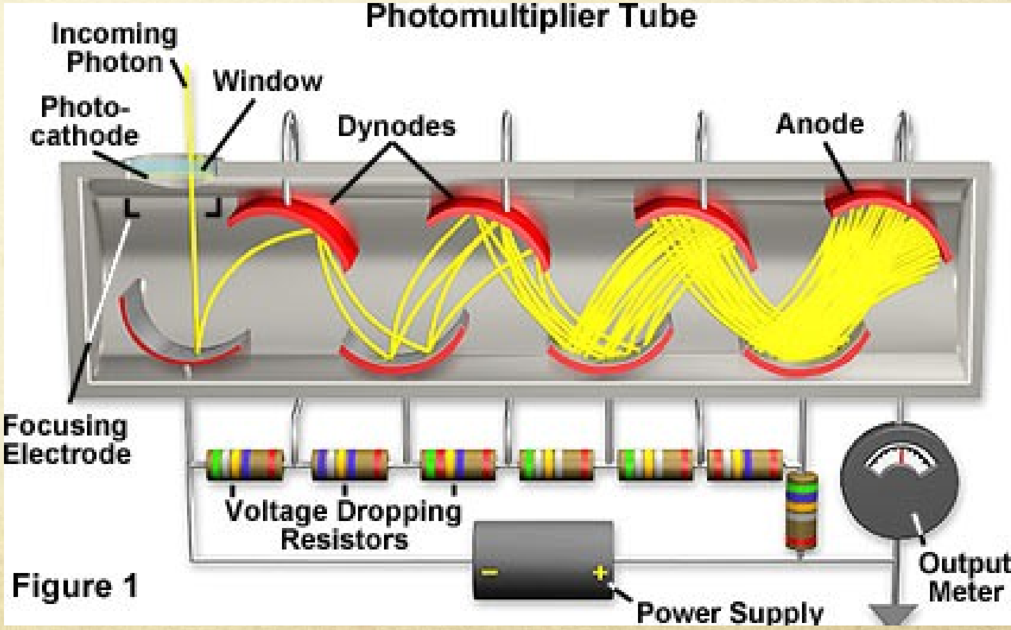
Particle ID is a broad topic as well with a wide variety of tools that it is good to be familiar with.

Backup

Collecting light

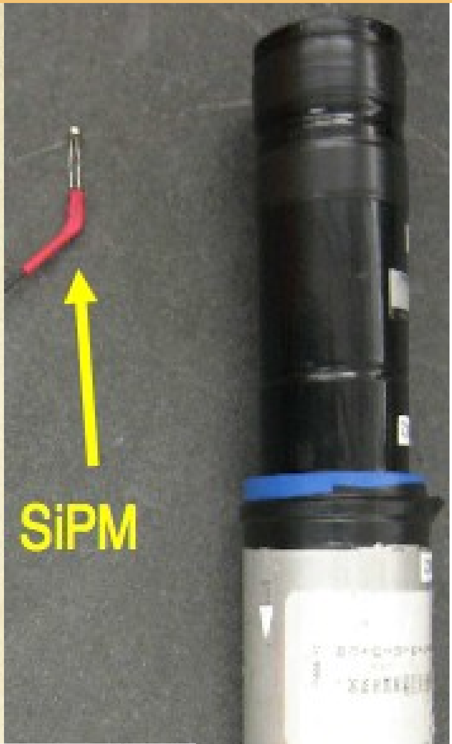
- Cerenkov light and scintillation light needs to be collected somehow. There are now many detectors which can do that.
- Photo-multiplier tubes (PMT's) have been around for 50 years and are still used in many applications:
  - A photon hits a photocathode liberating an electron which is accelerated to the first dynode where it has enough energy to eject additional electrons which free more electrons at the next dynode and so on.
  - ~10 stages and gains of 10^6

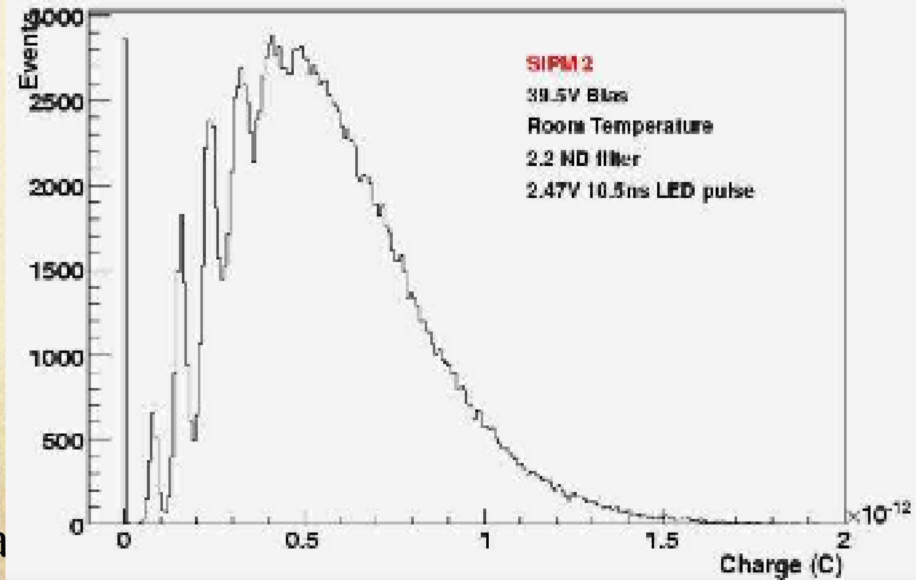
- Great efficiency and resolution
- Bulky, pricey, high voltage (>1kV), don't work in magnetic field



Other light measuring devices

- The last 15 years have seen many other devices:
  - Multianode PMT divides up the PMT for finer resolution (less bulk) with up to 32 outputs.
  - Silicon devices are now very important.
    - Photodiodes (no amplification), Avalanche photodiodes (APD), and hybrid photodiodes (HPD).
    - Now Silicon Photomultiplies (SiPM) are better than PMTs in every way
    - Lower cost, work in magnetic fields, better resolution, smaller, less power, lower voltage, etc.



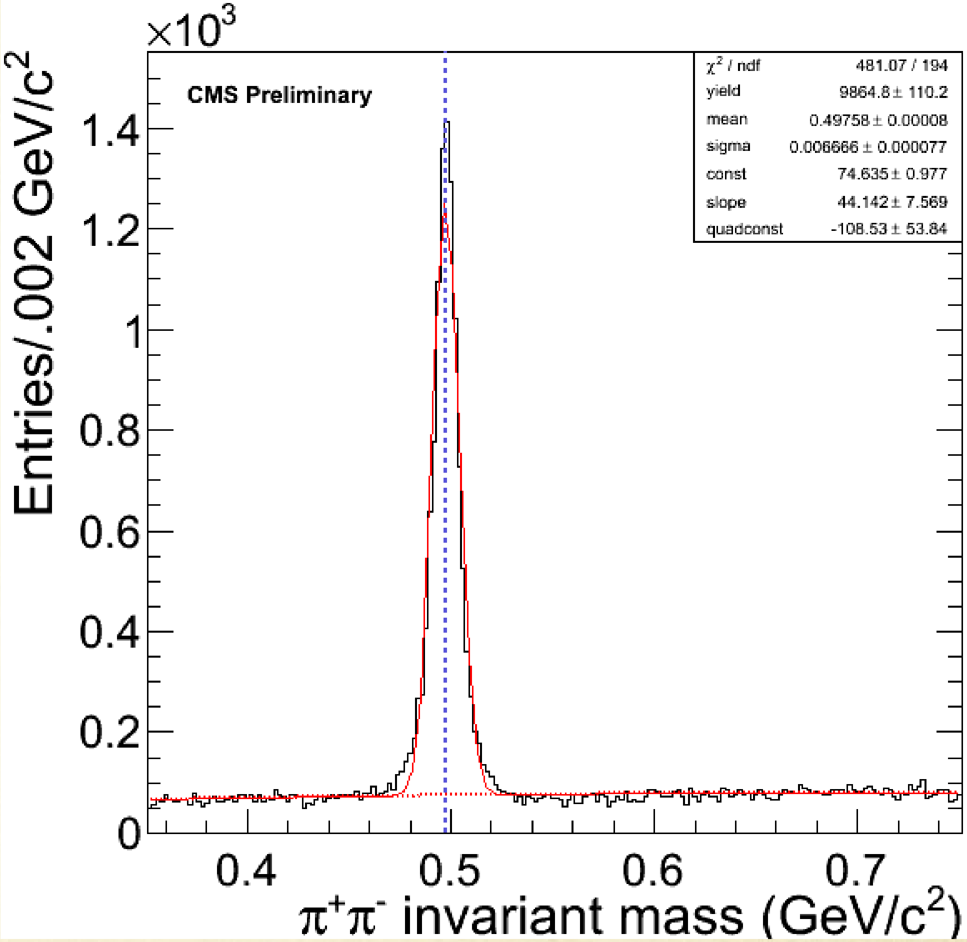


Invariant mass

- If a particle decays, we can try to reconstruct what it was.
- Take the decay products (such as two opposite charged pions) with momentum measured by the tracker.
- Einstein's energy-momentum relation and conservation of energy and momentum allow us to determine the mass of the parent particle.
- For the parent particle we have Einstein's relation: $E^2 = p^2 + m^2$
- We use conservation of energy ($E=E_1+E_2$) to get the energy and conservation of momentum ($\vec{p} = \vec{p}_1 + \vec{p}_2$) to get the momentum.
- Then just solve for mass: $m = \sqrt{E^2 - p^2}$

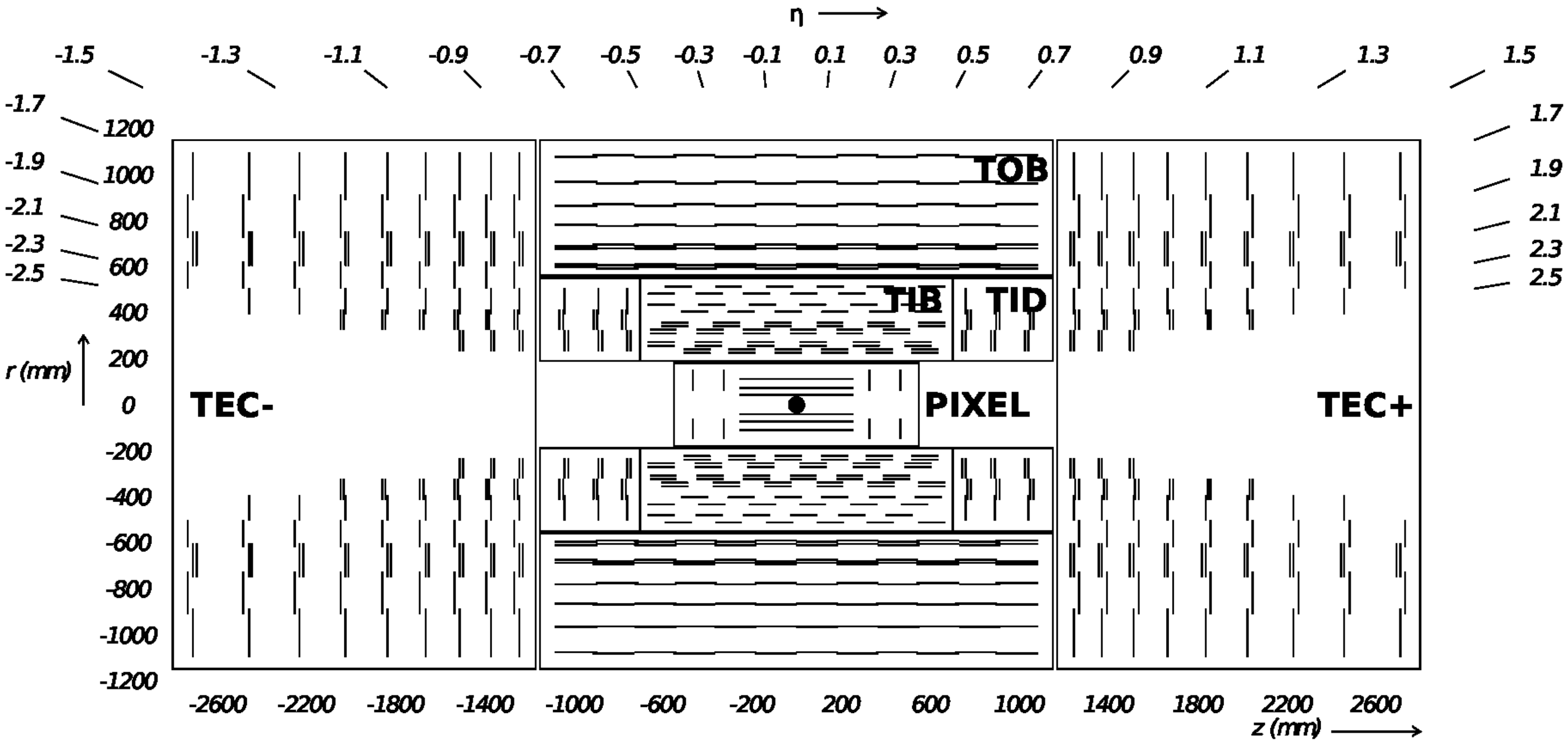
Reconstruction of K_S^0 particle

- In the data we have about 25000 possible candidates for which we calculate the invariant mass and put the result in one of the “bins” of the histogram (black).
- The “peak” occurs around a mass of 0.497 GeV/c^2 (blue) which is known to be the mass of the K_S^0 particle.
- We fit the histogram (shown in red) and find a signal yield of 9865 ± 110 events.



Even without “seeing” a K_S^0 we are able to infer the existence of ≈9900 of them with this technique.

CMS Tracker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