Detectors

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Introduction

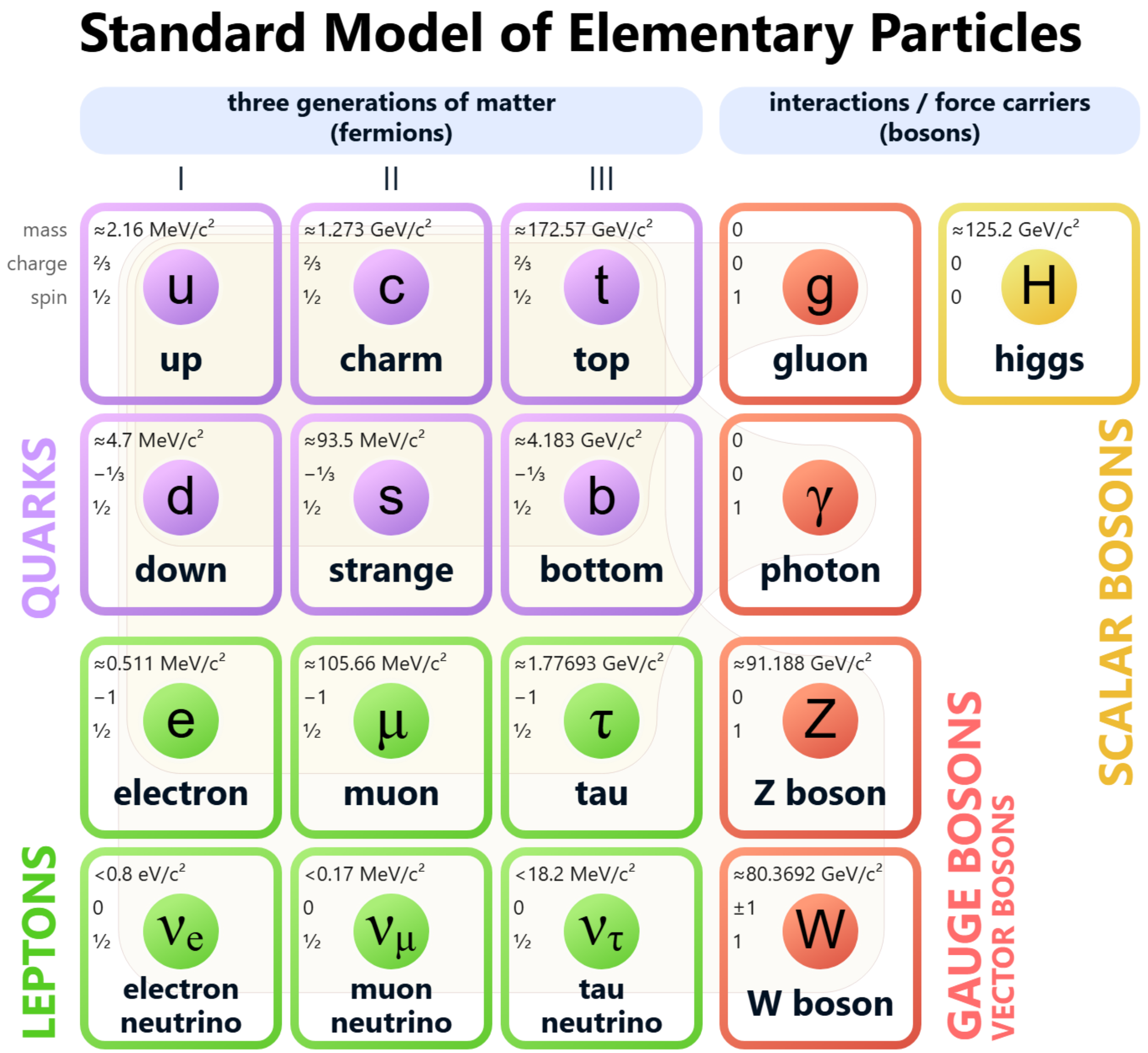
- Undergrad at University of York.
- A year in industry at CERN working on the LHCb scintillating fibre (SciFi) tracker.
- Now doing a PhD at the University of Liverpool (but based at CERN).
- I work on the monitoring and controls for the services for LHCb SciFi and on the planned upgrade of the FASER experiment for Run 4.

Why are Detectors Useful?

- We have a model that describes how particles behave.
  - Called **the standard model.**

- Physicists obviously love discovering new particles…
- But making sure our existing model is describing things correctly is also very important!
  - Stress testing our model, how does well does it describe very rare processes.

- To do either we need to be able to see particles and their physical processes.
  - This is where we need a detector.



What Do We Want To Measure?

- We want to know…
  - The trajectory
  - The type of particle
  - Energy of the particle

- ☐ Position
- ☐ Velocity

} **Track**

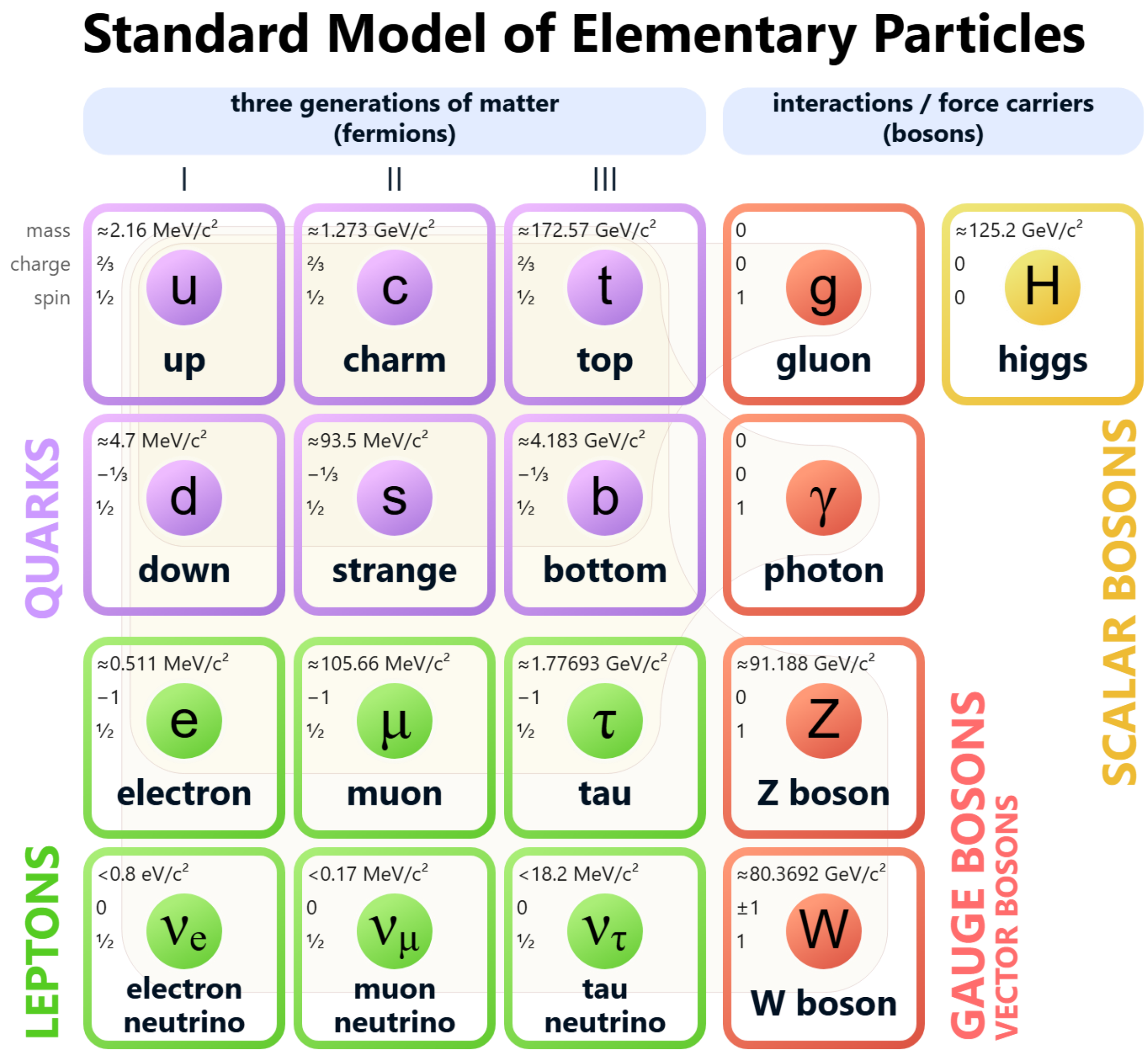
- ☐ Momentum
- ☐ Charge
- ☐ Energy

} **Particle ID**

But how???

Particles interact with matter!

As we cannot observe the particle directly we can observe how it interacts.

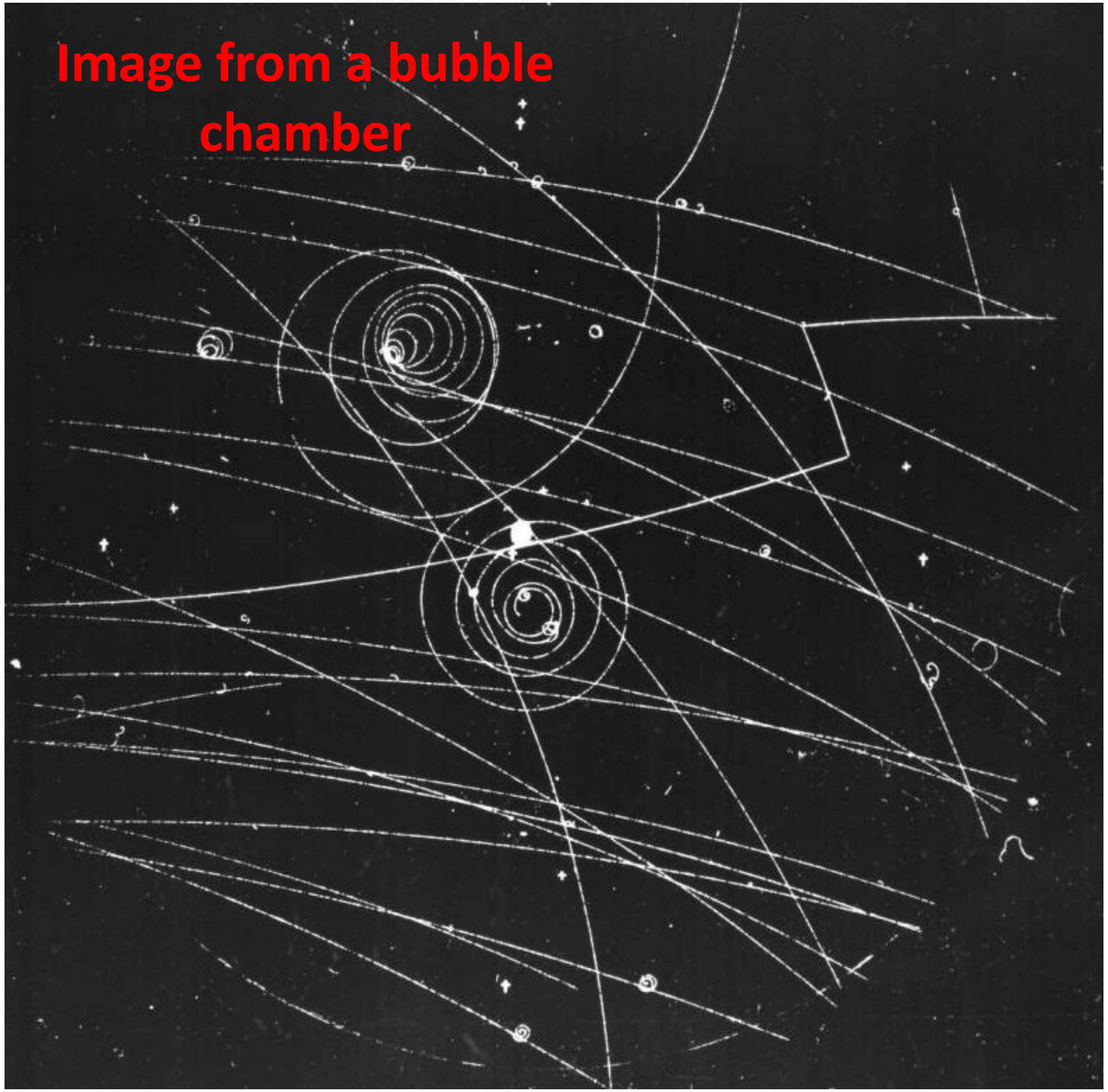


Interactions With Matter

- A particle travelling through a volume of matter will interact in different ways depending on its energy.
- **EM interactions** will result in the excitation of an electron or **ionisation.**
- **Ionisation** is the basis for detectors!

- The first detector invented was a **cloud chamber.**
  - **Invented in 1911 by Scottish physicist Charles Thomson Rees Wilson.**
  - Looking at how clouds form.
  - Particles ionising the alcohol vapour in the volume left visible tracks!

- Later the **bubble chamber** was invented.
  - **Invented in 1952 by American physicist Donald Arthur Glaser**
  - Filled with a liquid (e.g. liquid hydrogen).
  - Denser than vapour…
    - More interactions per unit volume.
    - Energy loss creates bubbles.

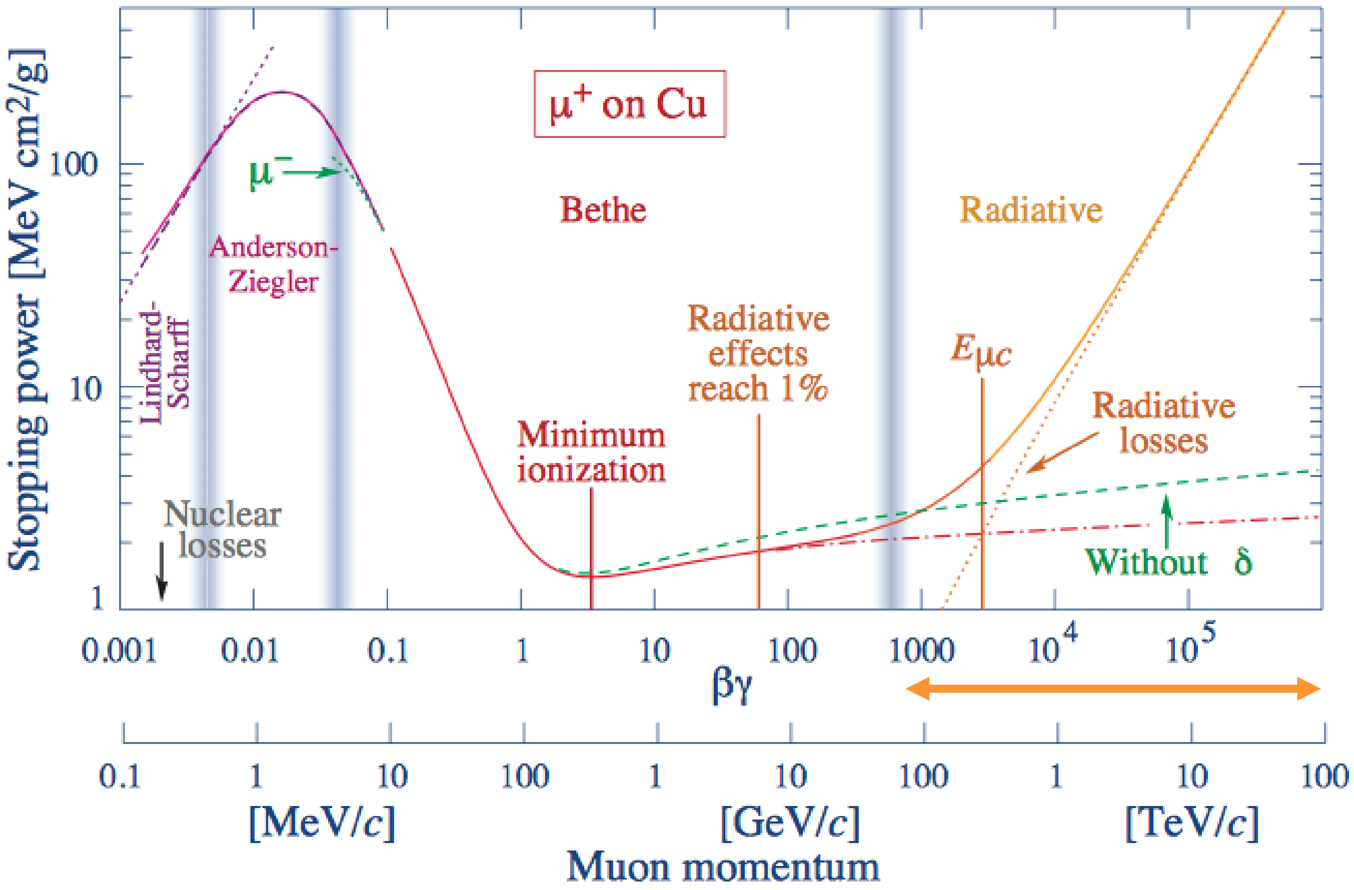


Interactions With Matter

- As you could see from the tracks, **a particle interacts a huge number of times as it travels through a volume of matter**.
  Focusing on each individual interaction is not an option, we want to know how a **particle deposits energy along its track**.
- The Bethe-Bloch equation tells us the **stopping power** (how a particle deposits energy along a distance).

$$-\frac{dE}{dx} = nZ_{mtl}\left(\frac{Z\alpha\hbar c}{2v}\right)^2\left(\frac{4\pi}{m_e}\right)\left(\ln\left(\frac{2m_e v^2}{I\left(1-\frac{v^2}{c^2}\right)}\right)-\frac{v^2}{c^2}\right)$$

- **Stopping power ∝ Z** (mass number of material)
- **Stopping power ∝ 1/β²** (β is the fraction of the speed of light the particle is travelling at).
  - The faster a particle is travelling the less energy it deposits along its path.
- Past a certain energy, particles can lose kinetic energy through radiative losses (Bremsstrahlung radiation).



Interactions With Matter

- **Bremsstrahlung radiation (braking radiation)** is emitted from a particle when it interacts with the electric field from a nucleus.
  - **Some kinetic energy** of the particle is converted to an **emitted photon** when the particle changes direction due to the field.

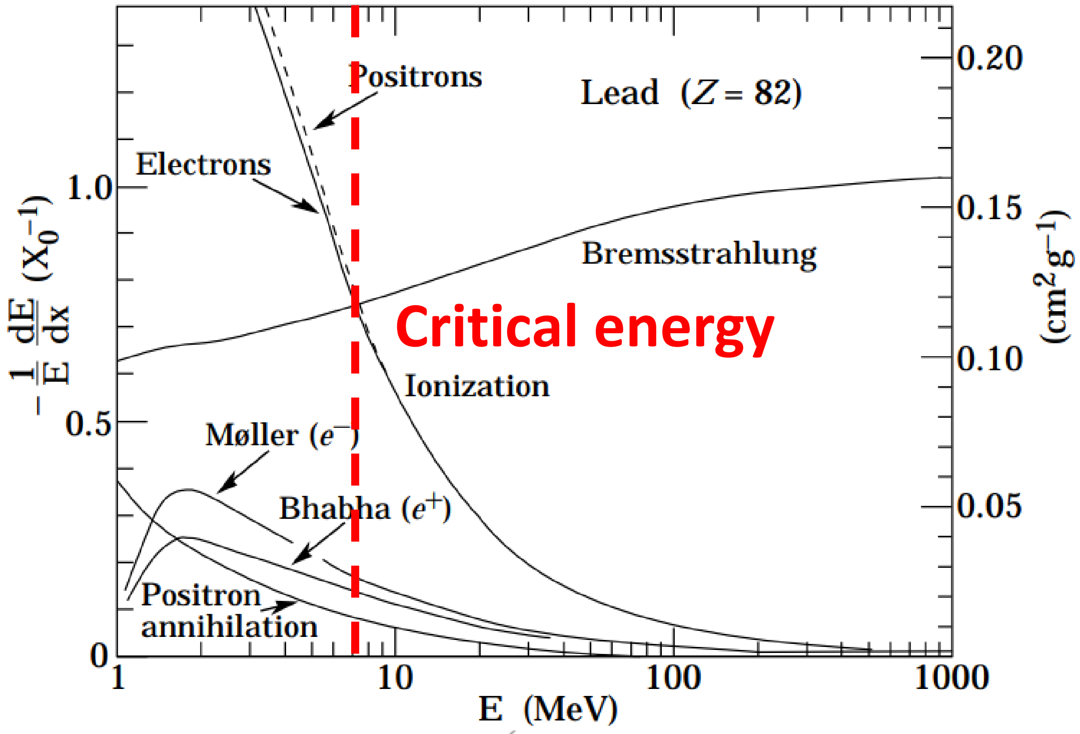
- **This process dominates above the critical energy.**
  - For electrons, the critical energy is 5-20 MeV.

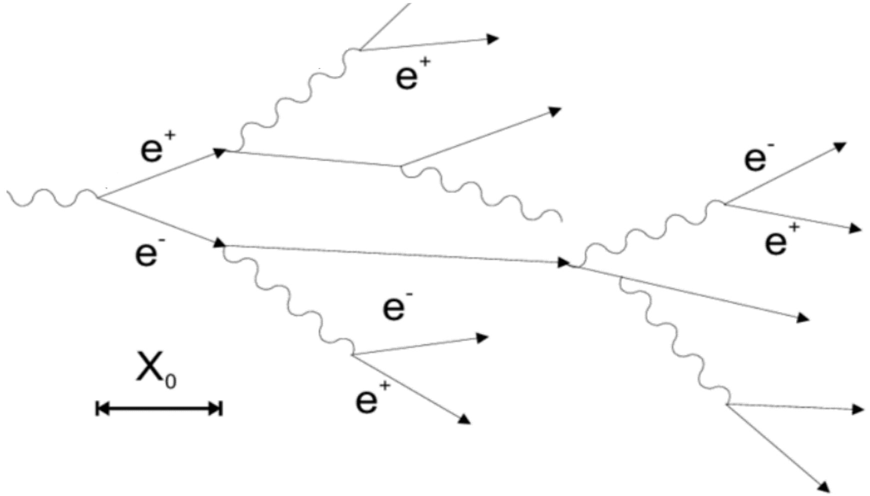
- The cross-section for interaction:

$$\sigma \sim \frac{Z^2 \alpha^3}{m^2}$$

  - **$\sigma \propto Z^2$** (mass number of the material)
  - **$\sigma \propto 1/m^2$** (mass of the particle)

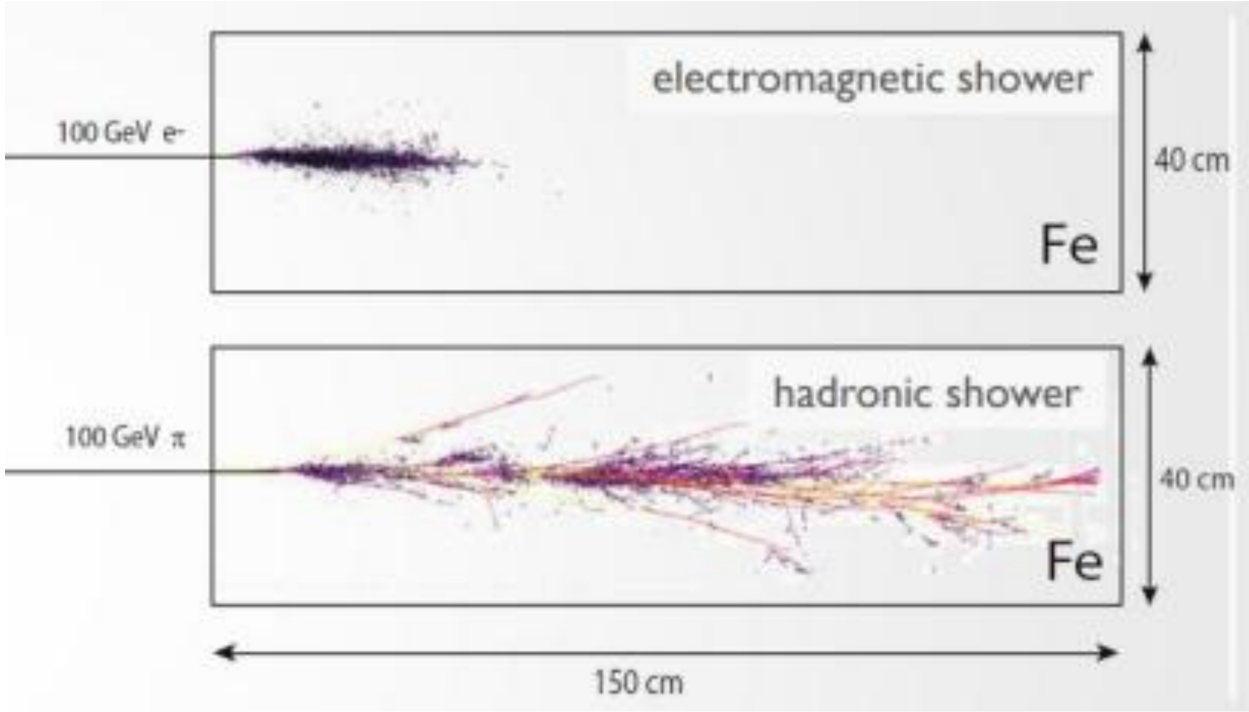
- The **bremsstrahlung** then can produce EM showers where the photon interacts via pair production.
  - The electron-positron pairs undergo bremsstrahlung and this continues in a cycle until the photon energy falls below the threshold for pair production to occur (1.022 MeV).

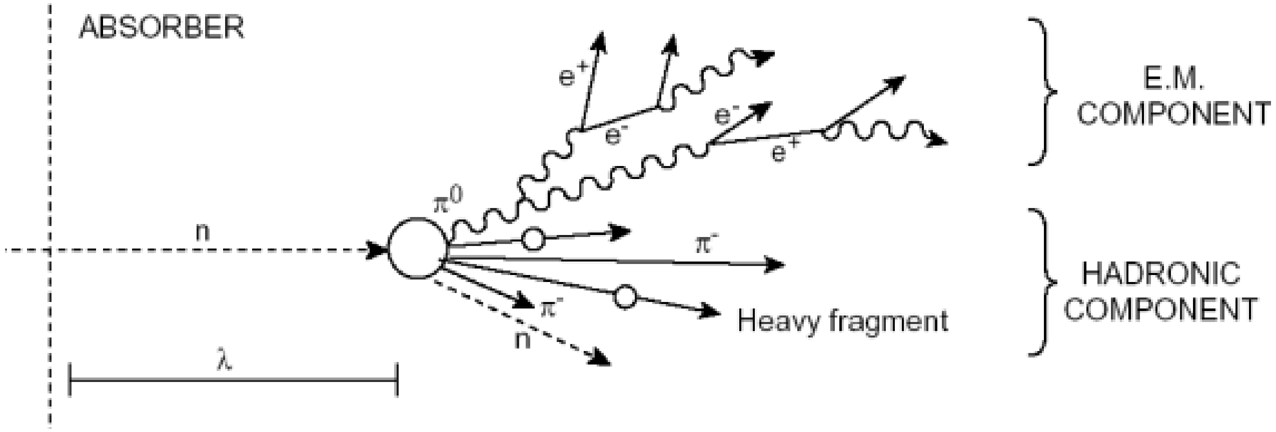




Interactions With Matter

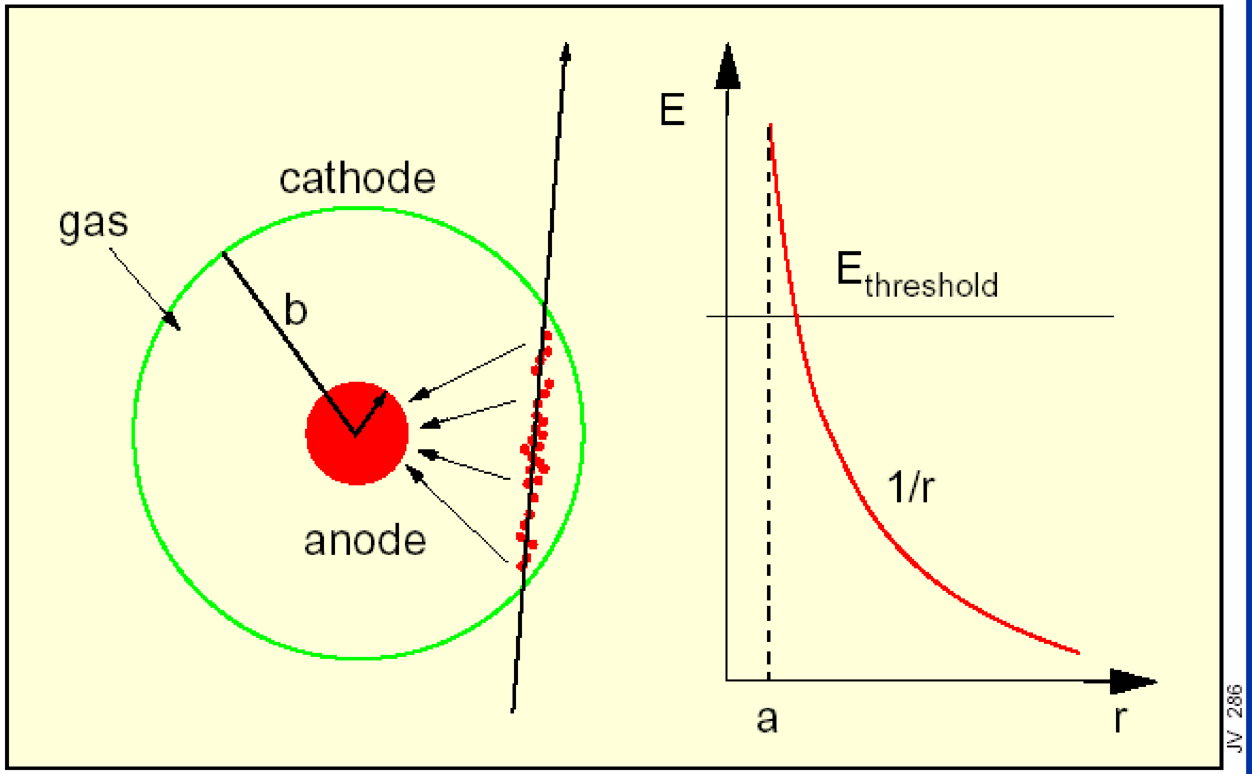
- **Hadronic showers are more penetrative than EM showers.**
- **Started through inelastic nuclear interactions**
  - Hadronic showers also have an EM component in addition to the hadronic component.
    - When neutral pions decay to 2 photons.
- As they are more penetrative, hadronic calorimeters typically need much more material.
- The shower ends when the energy is too low to make anymore pions.





Gas Detectors

- Gas volumes can be used to observe charged particles that ionise gas particles as they pass through.
- Running a current carrying wire (anode) through the volume will induce an electric field.
  - A charged particle will ionise an atom creating an electron-ion pair.
  - The electron drifts to the anode and the ion to the cathode.
- We see the ionisation in a charge pulse.
  - But if we only have the electron-ion pairs from the initial ionisation we have a tiny signal…
- To get more electron-ion pairs we need more ionisation!
  - Increasing the strength of the electric field gives the electrons more energy to have further ionisation.
  - If the field is strong enough an avalanche of electron-ion pairs can be made.
    - This is called a Townsend avalanche.



Gas Detectors

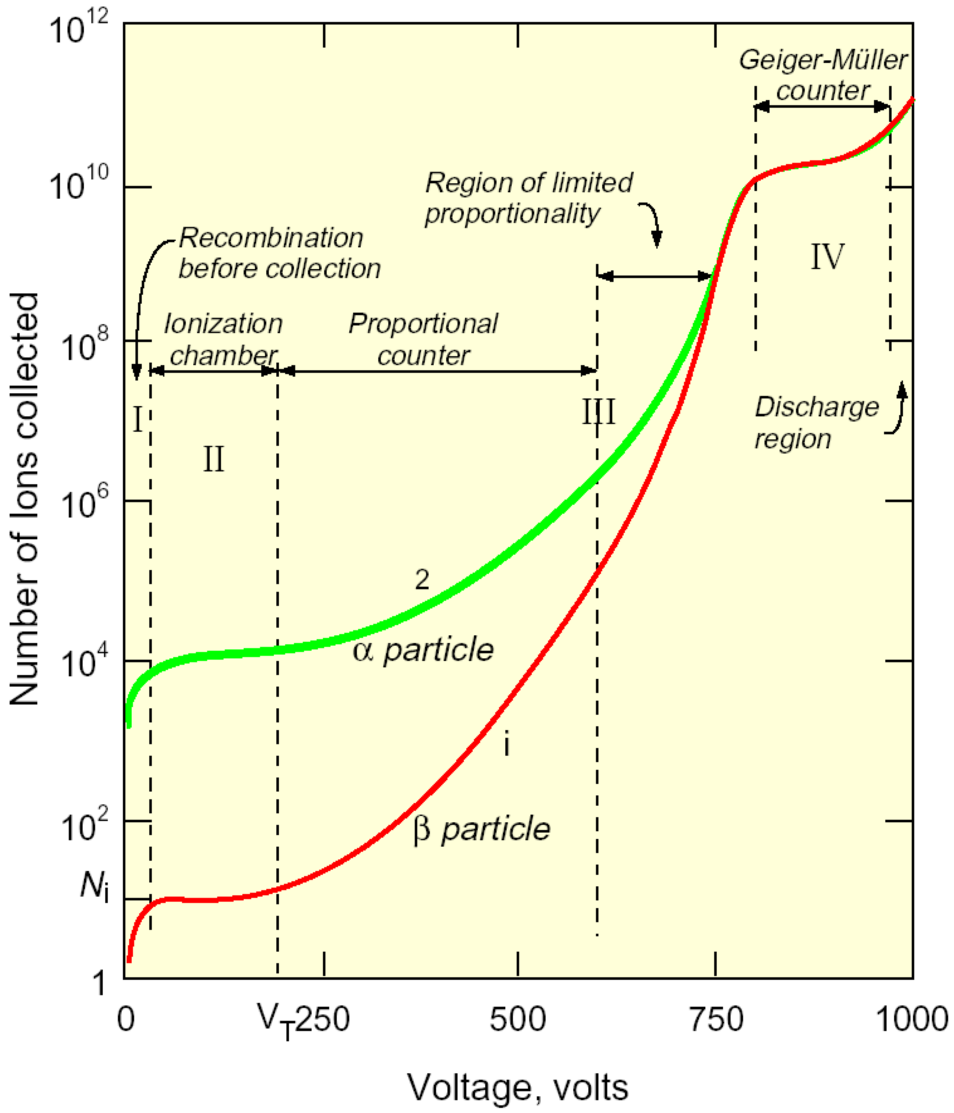
- Gas detectors can be operated in different modes depending on the supply voltage (and therefore strength of the E-field).

I. Very low field so basically no charge collection.

II. Ionisation mode
- charge collection but no amplification

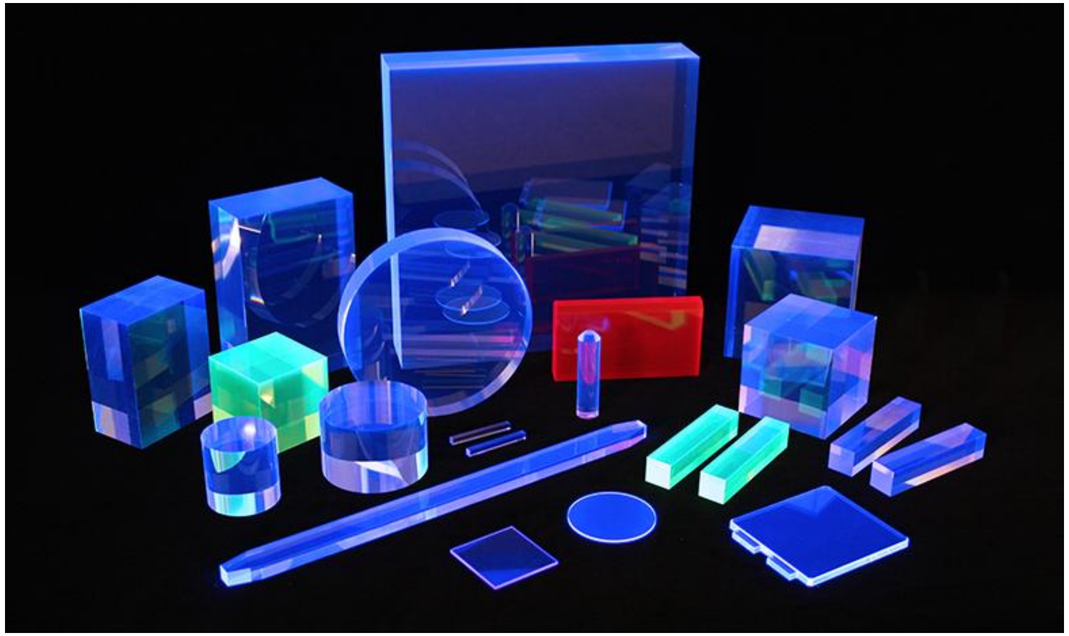
III. Proportional mode
- Charge amplification proportional to the energy absorbed by the incident charged particle.

IV. Geiger mode
- Full ionisation of the gas in the volume.
- The signals will therefore all have the same size, independent of the original charge.



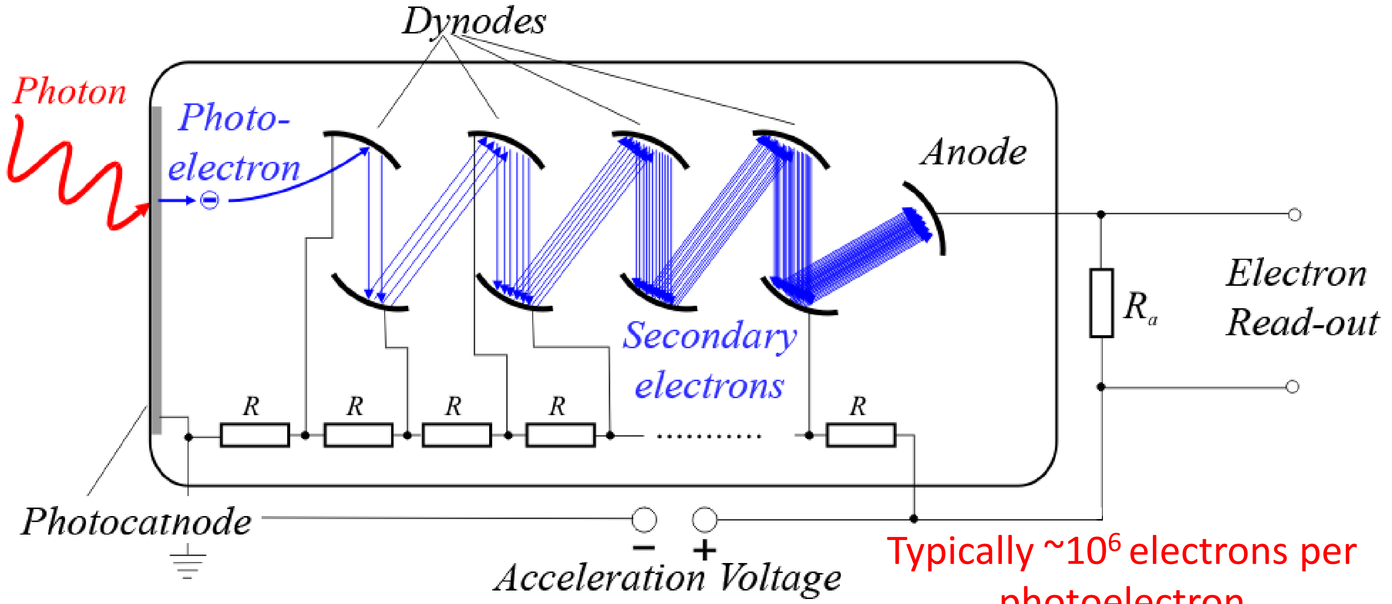
Scintillators

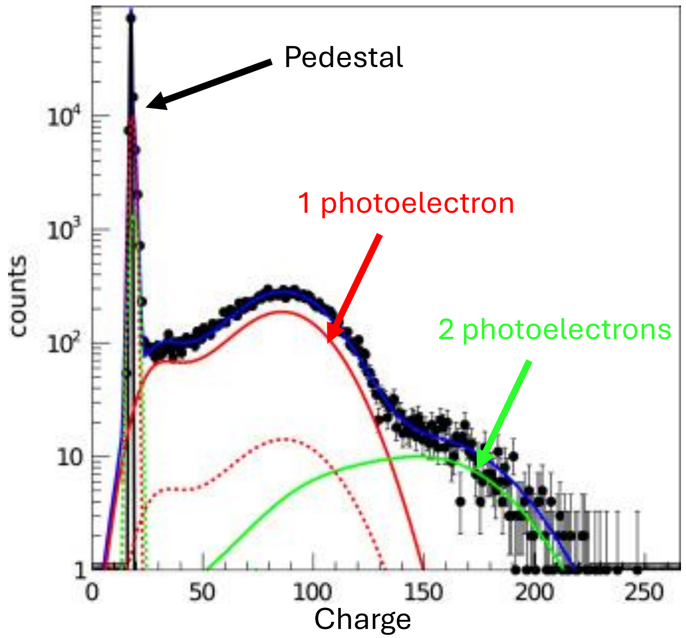
- Some materials emit light when a charged particle interacts with it.
  - These are called **scintillators**.
- There are so called **organic** (e.g. doped polystyrene etc.) and **inorganic** (e.g. NaI, CsI etc.) scintillators.
- When a charged particle passes through a scintillator:
  1. Some energy will be absorbed and promote an electron to a higher energy state.
  2. The electron will de-excites back down to the ground state and floresces (releasing a photon).
- Crystal scintillators (inorganic) are only doped with a scintillator (e.g. thalium) as they are transparent to the scintillated light.
- But there needs to be a way to measure the light.
  - This is where the photoelectric effect is very handy!



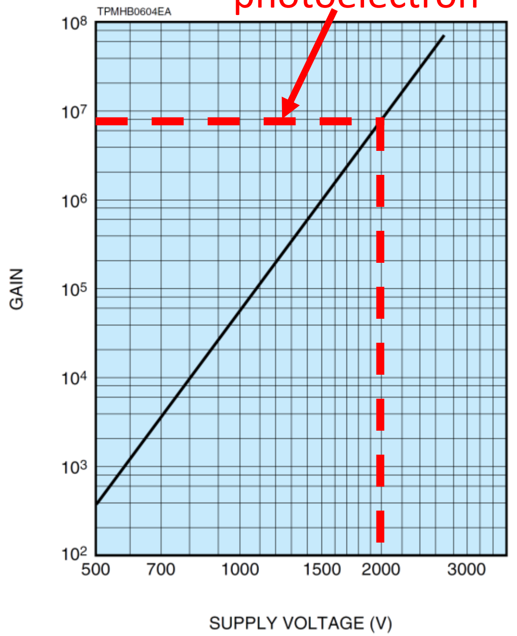
Photomultiplier Tubes

- A **PhotoMultiplier Tube (PMT)** can be used to detect a photon and convert this to an electronic signal.
- A photon incident on the photocathode will emit a photoelectron via the photoelectric effect.
  - One electron is not enough to readout…
  - So we need some amplification.
- A PMT often has 8 to 14 **dynodes**.
  - A dynode is supplied a voltage to create a potential to accelerate an electron towards it.
  - Dynodes are typically coated to have a good likelihood of secondary emission of electrons.
    - E.g. Beryllium oxide
  - Each dynode can emit typically 4 electrons from an incident electron (but this can vary from ~3 to 50, this is the gain of a dynode).
- This results in a **typical gain of the PMT is around 1 million electrons** from a single photoelectron.
  - Now this is a big enough signal for readout electronics!





Typically ~10^6 electrons per photoelectron



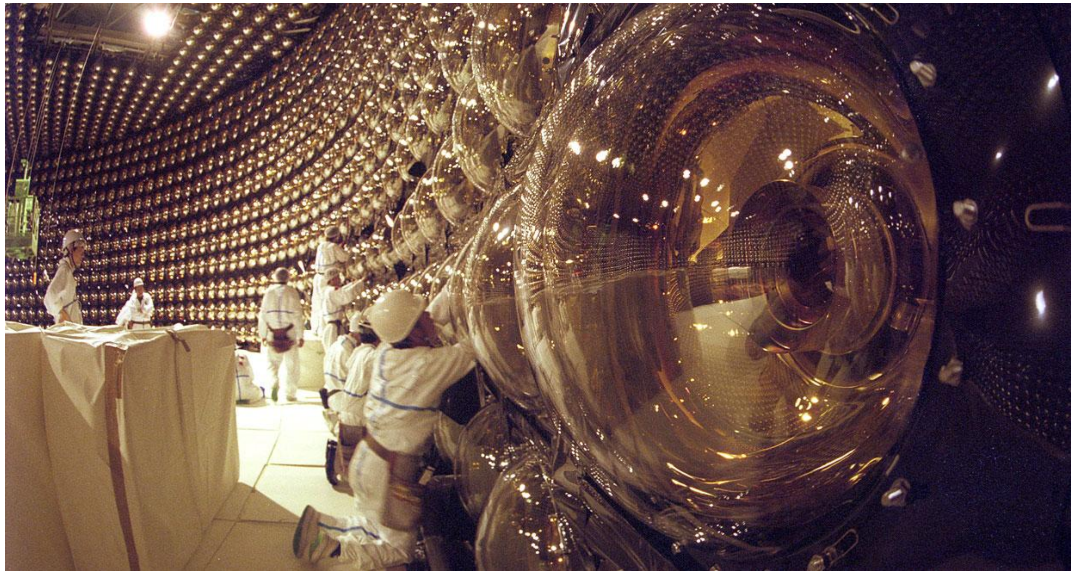
Photomultiplier Tubes

Pros:

- Radiation hard.
- High gain (very easy to readout the signal).
- Low noise per area the detector covers.
- Temperature insensitive.
  - Doesn’t need cooling which adds a lot of material and cost to a detector.

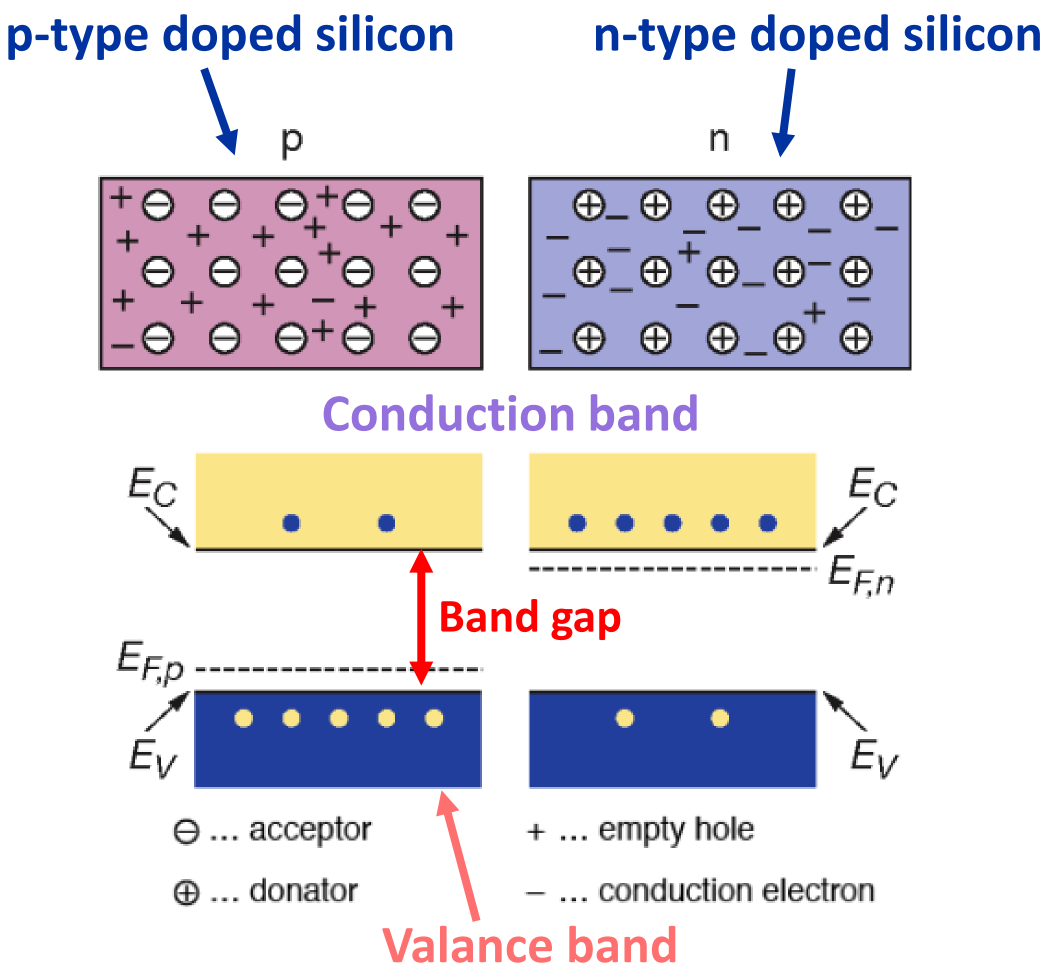
Cons:

- A PMT is expensive!
- Requires high voltages.
- Gets noisy as vacuum degrades over many years.
- Very sensitive to magnetic fields.
  - Even Earth’s magnetic field!
  - Can be shielded to stop electrons wandering away from the dynodes…



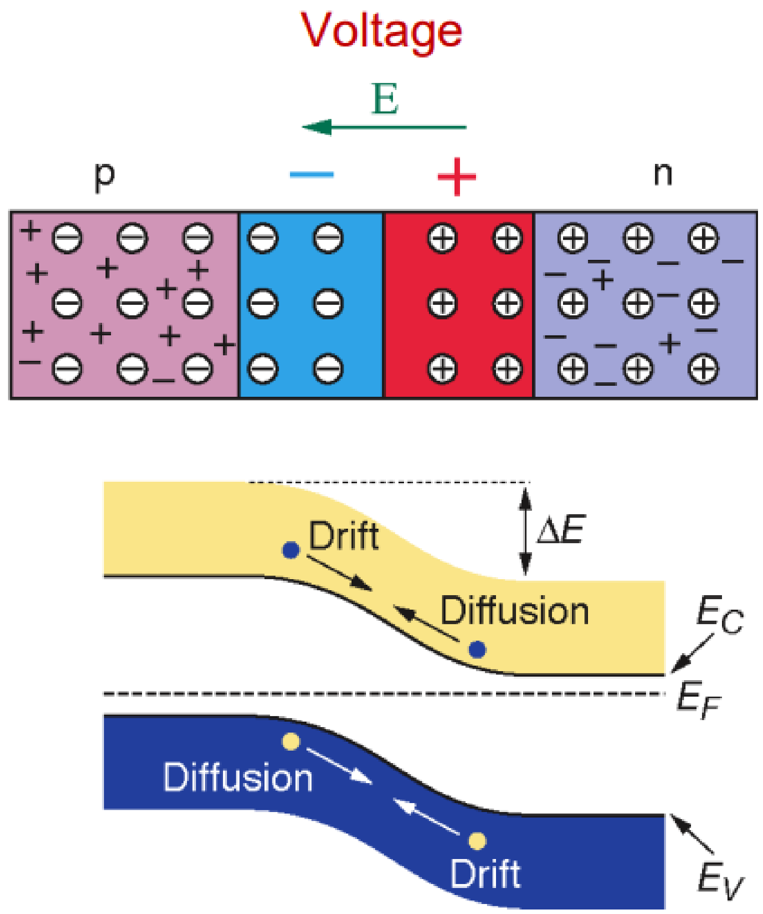
Solid State Detectors

- In areas with **high track occupancy** (many particles passing through the detector), we need a detector that can induce more charge and allow the charge to move to the cathode quickly.
- Semiconductors have a band gap between the occupied valance band and the conduction band.
  - Therefore, an electron needs to be excited to the conduction band.
  - However, this is not exclusive to a charge particle ionising a silicon atom…
    - Electrons can be promoted via thermal excitations which makes thermal noise an issue for solid state detectors.
- Many detectors utilise **reverse biased pn-junction diodes**.
  - A section of Silicon doped with atoms with an additional, loosely bound electron (n-type doped).
  - Another section with an atom with one less electron (p-type doped).

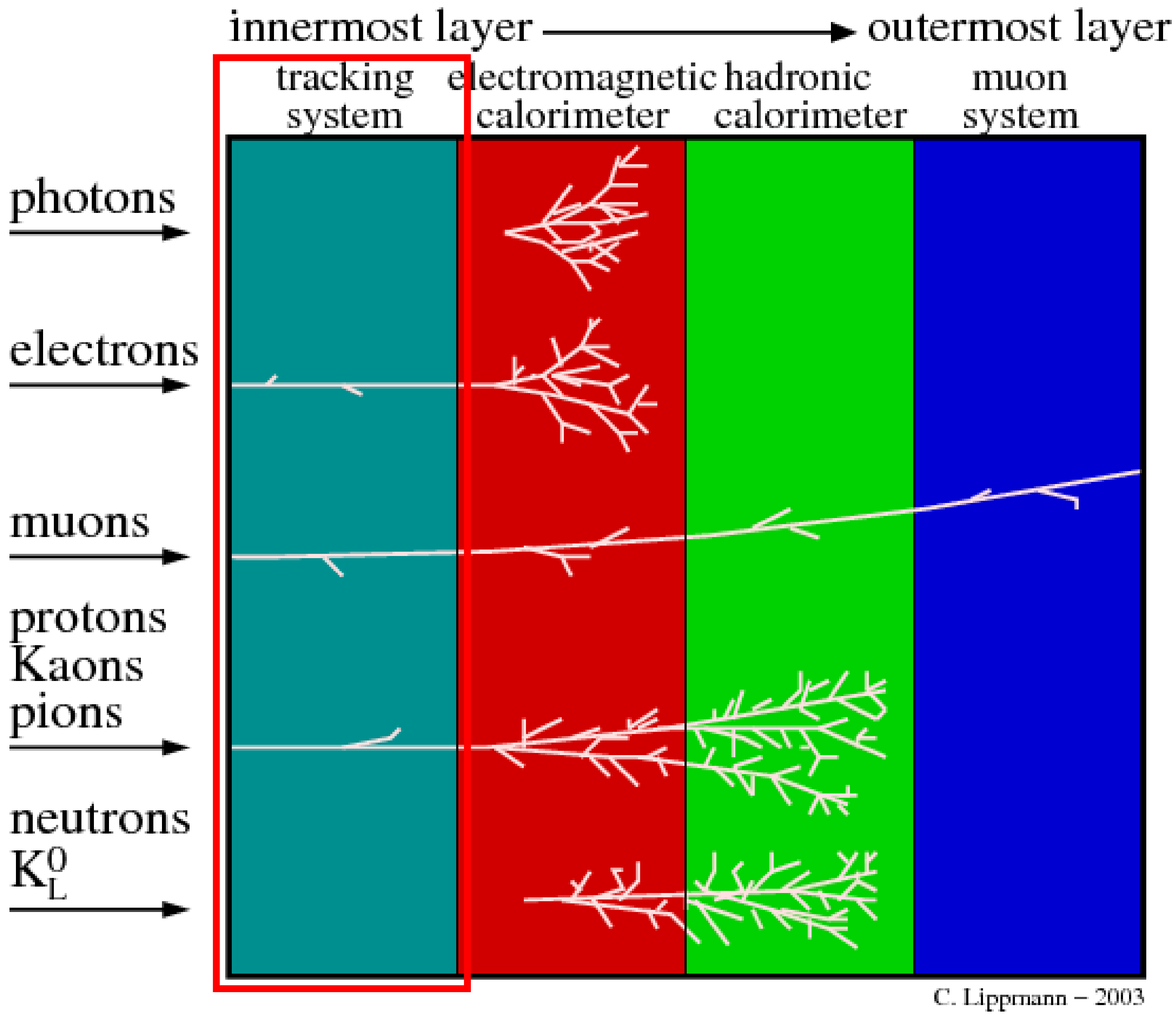


Solid State Detectors

- Applying a positive current to the n-type silicon created a reverse bias which increases the gap (the depletion region) created by the free electrons and holes in the respective doped silicon.
  - This is a reverse bias.
- There is a strong electric field in the depletion region.
  - A charged particle passing through the depletion region will interact and ionise an atom, creating an electron-hole pair which drifts towards the electrodes and can be detected.
- Many diodes can be placed together to form a detector.
  - Used for high precision tracking (as a detector is made from small segments (pixels or strips)).

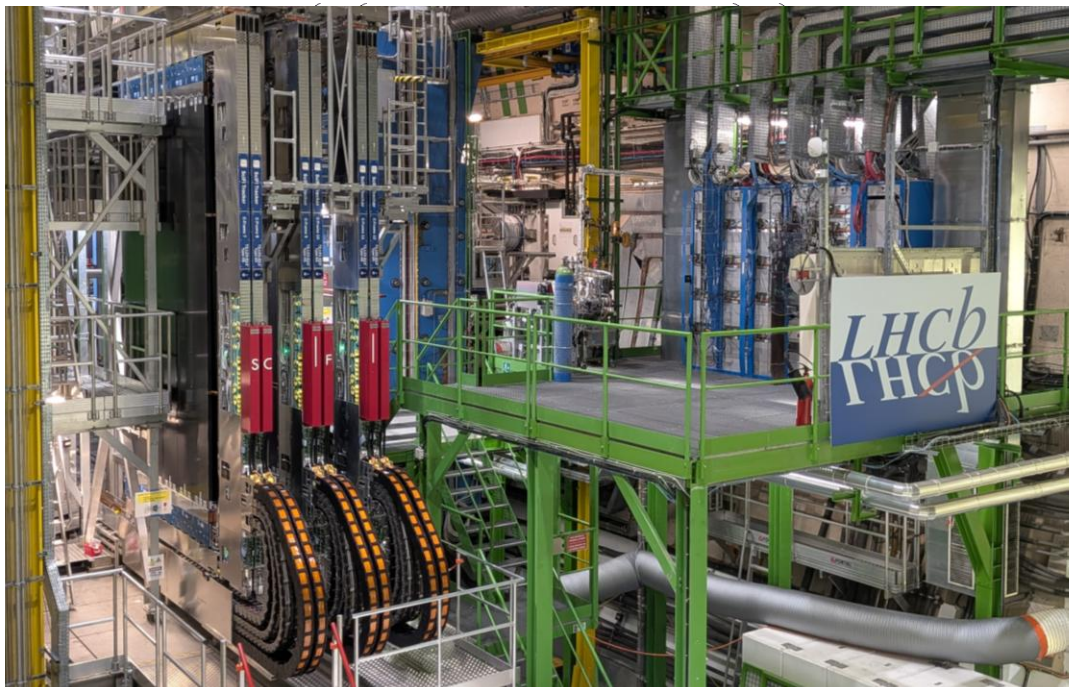


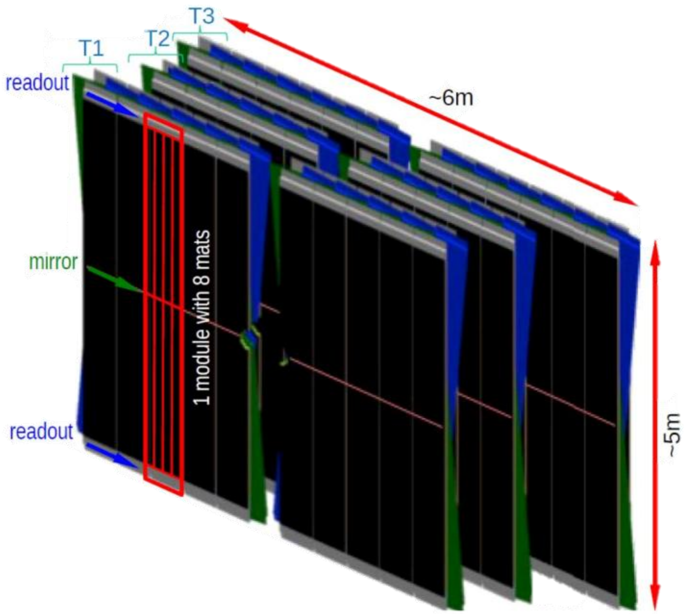
Typical Detector Layout



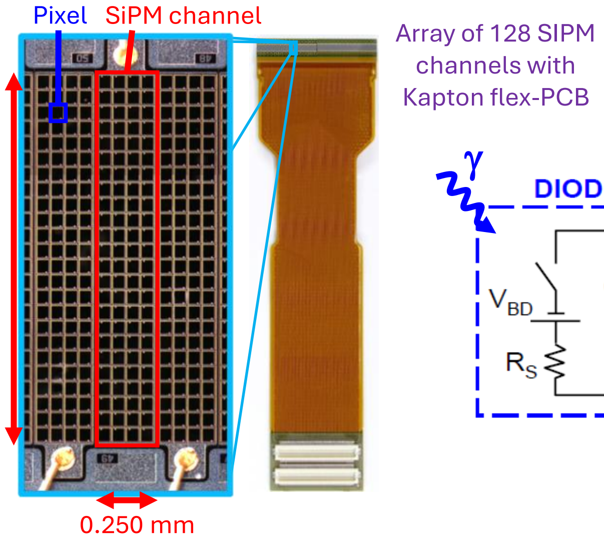
LHCb Scintillating Fibre Tracker

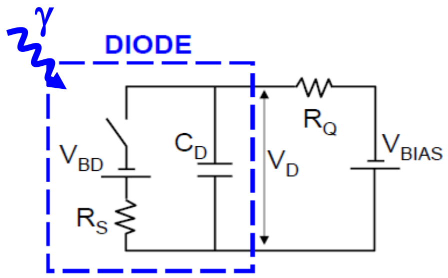
- **The Scintillating Fibre (SciFi) tracker** is the third tracker along in LHCb.
    - The detector has an area of 340 m².
- **SciFi uses layers of scintillating fibres** to make tracking layers.
    - 12 layers in total with some at ±5° to make stereo layers.
- **Scintillating fibres have a core** where a charged particle will interact with producing the scintillated light.
    - The fibres used are double cladded so light can propagate through the fibre via total internal reflection.
    - The light is collected at the very ends of the fibres.





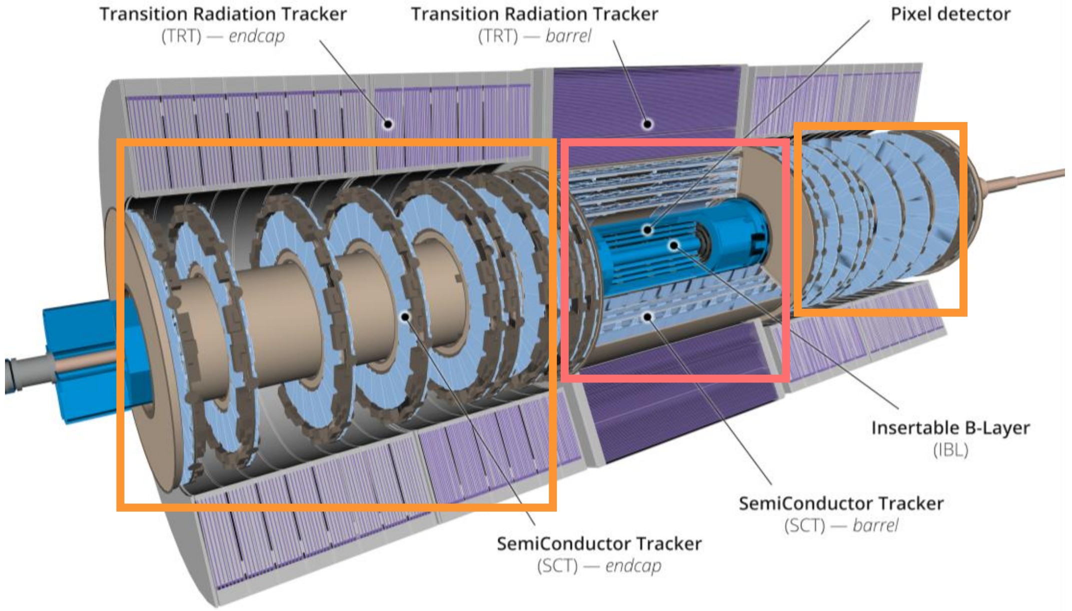
- Uses Silicon PhotoMultipliers (SiPMs) to digitalise the signal.
    - SiPMs are arrays of avalanche photodiodes (pixels) operated in Geiger-mode (all pulses the same height).
    - Pixels are 62 µm x 57 µm.
- SciFi has just over 500,000 channels.





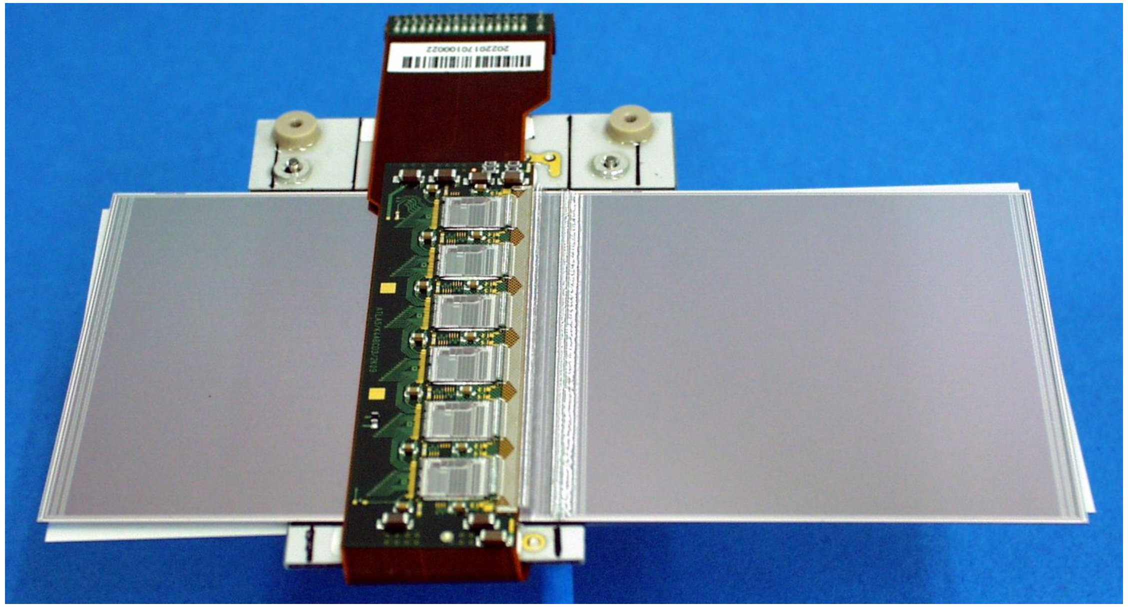
ATLAS SemiConductor Tracker

- The ATLAS SemiConductor tracker (SCT) uses silicon strip detectors.
  - Like if your camera had pixels that were very long in one dimension.
- A particle passing through ATLAS SCT passes through at least 4 layers of strip detectors.
  - This provides a position resolution of as good as 25 µm.
  - To cover all dimensions there are two parts with different geometries:
    - The barrel part of the SCT which wraps around the beampipe.
    - The end caps which cover the ends of the barrel.



Pros:
- Fewer channels to readout than using square pixels.
- Very radiation hard.
- Very precise tracking.

Cons:
- Very expensive per area.
- Cannot handle a high flux.
- Needs to be cooled.

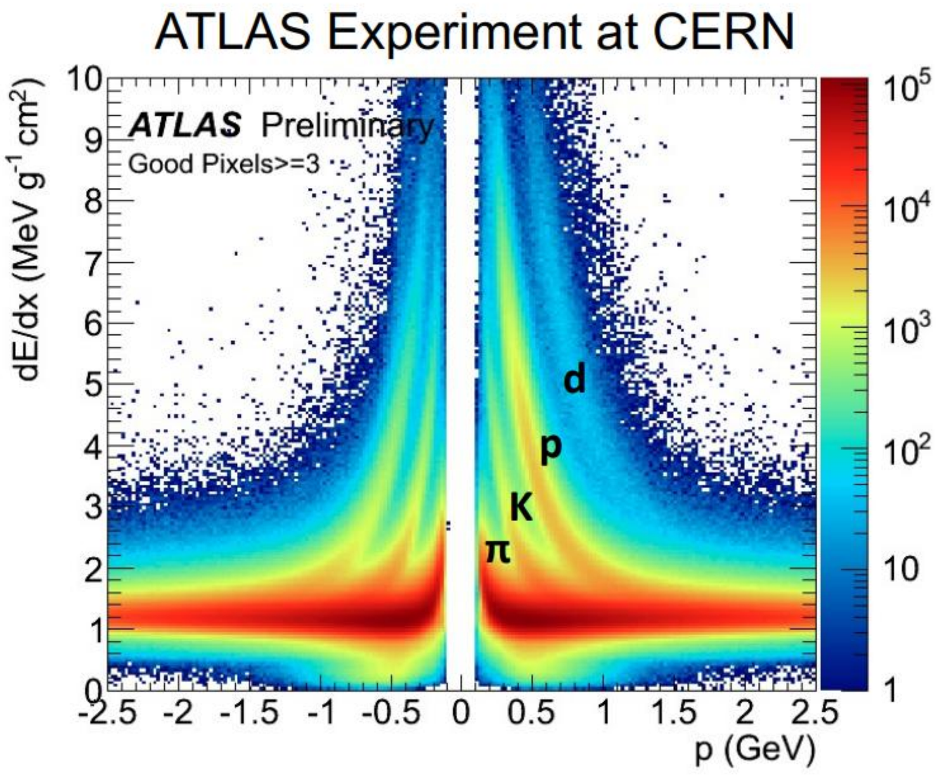


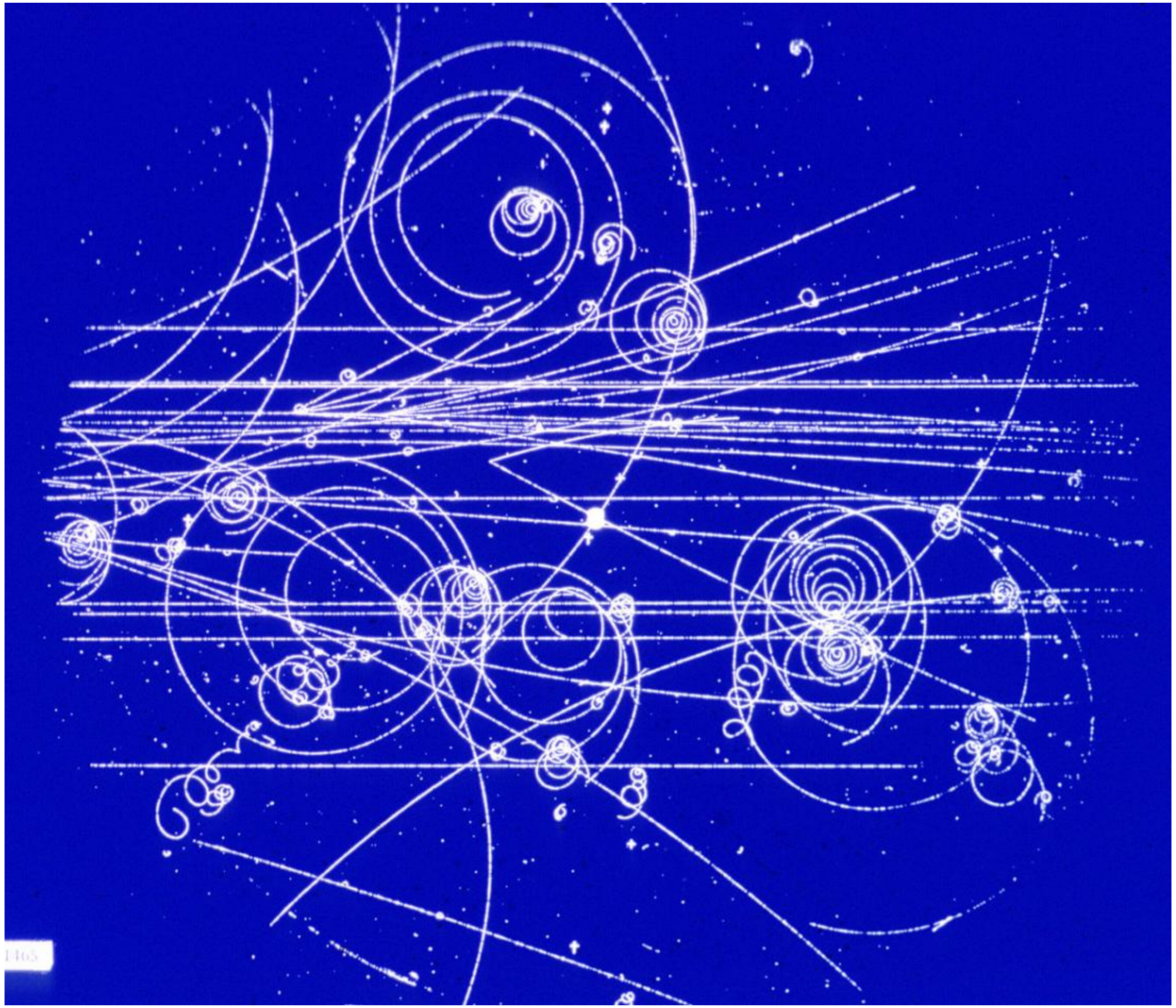
Charge Information From Tracks

- For **momentum and charge** information we can look at how a particle moves through a magnetic field.

$$r = \frac{mv}{qB}$$

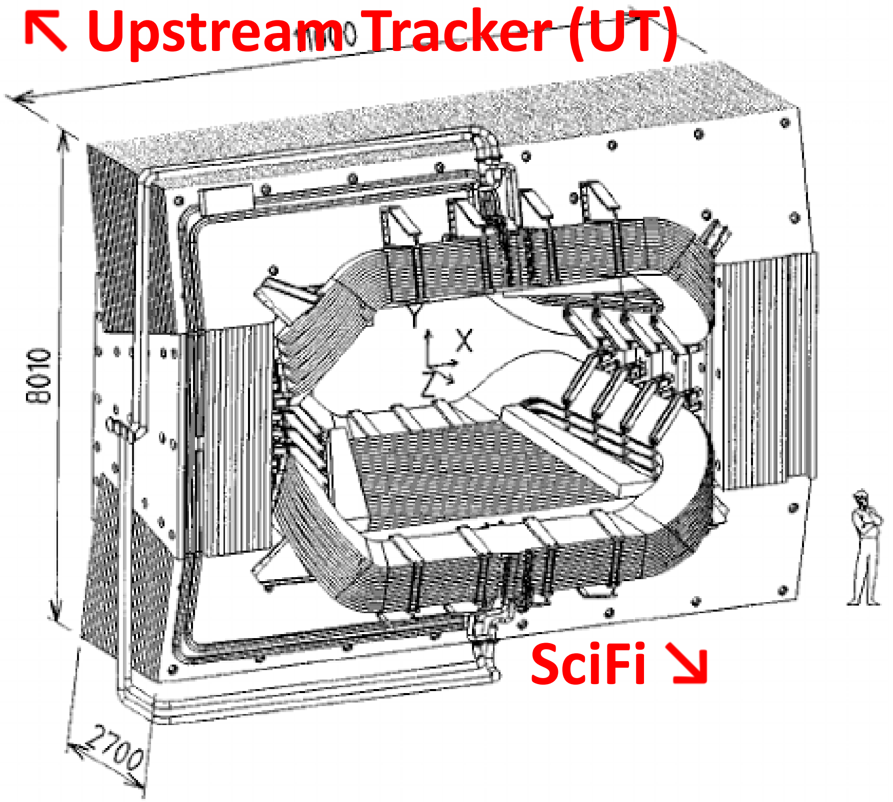
- How tightly a particle curls in a magnetic field tells us about the type of particle.

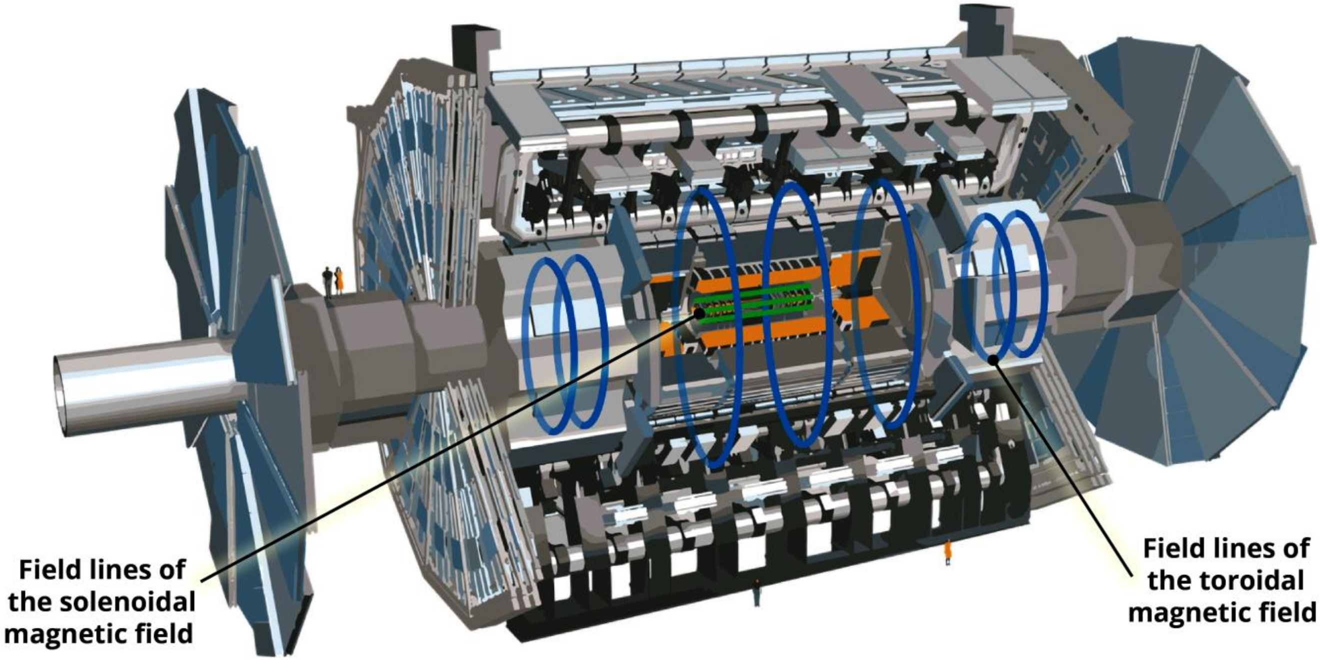




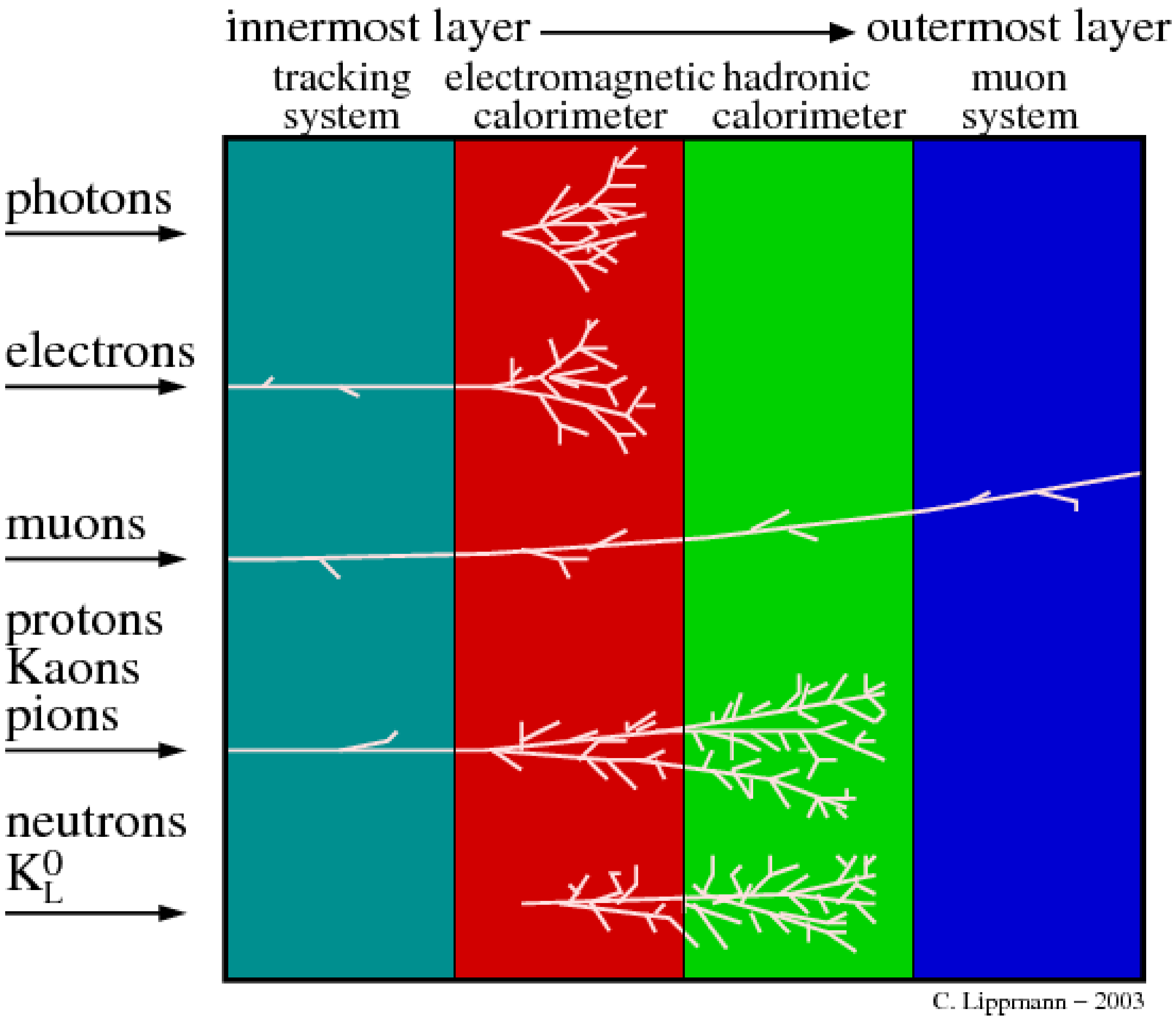
Magnets in Experiments

- LHCb has a dipole magnet in between two trackers (the Upstream Tracker (UT) and SciFi).
  - By using the tracks before and after they're bent by the magnet, the momentum of the particles is measured.
  - Tracks are split amongst the trackers in LHCb and are pieced together later.
- ATLAS uses superconducting magnets.
  - Solenoidal magnets in the center of the barrel (the Central Solenoidal Magnet).
  - Toroidal magnets in the barrel and for the end-caps.
- Solenoid has a 2 T magnetic field and the toroidal magnets have 4 T fields.
- Cooled to 4.5 K.





Typical Detector Layout

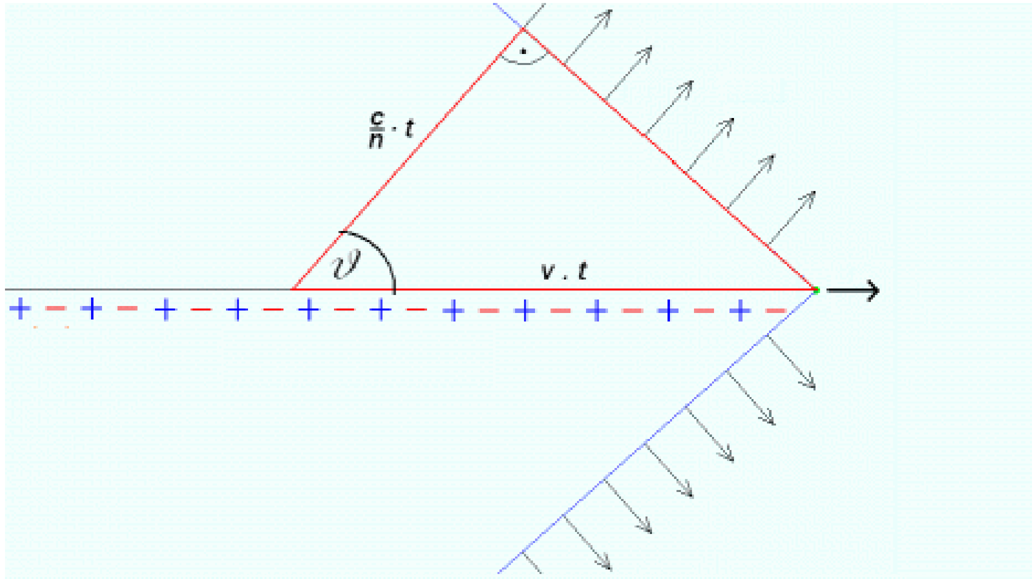


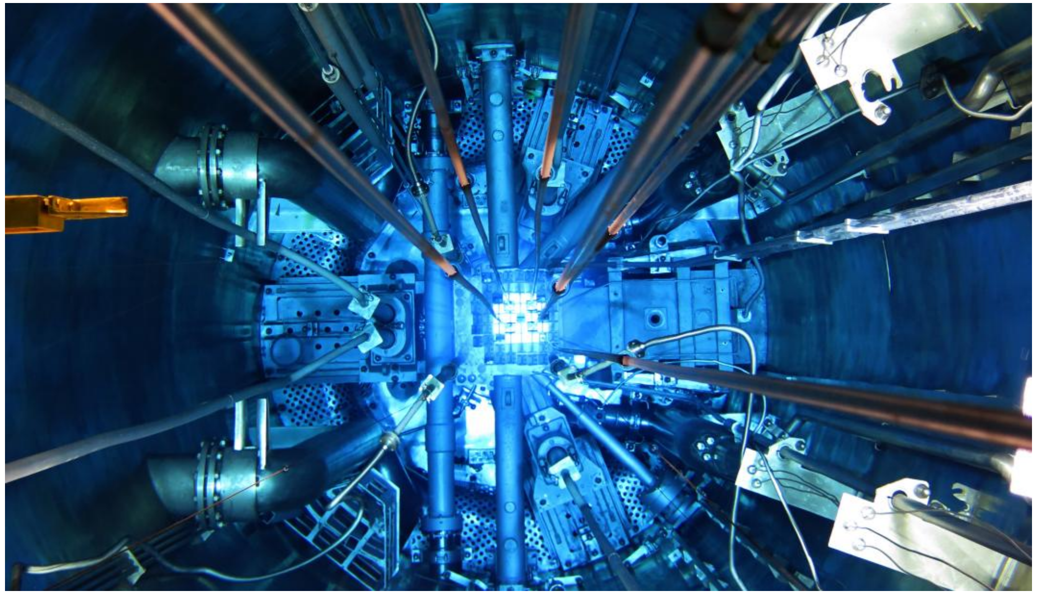
Cherenkov Radiation

- When a charged particle moves into a material and is travelling faster than the speed of light in that material, blue photons are emitted.
  - This is Cherenkov radiation.
  - **Like a sonic boom!**

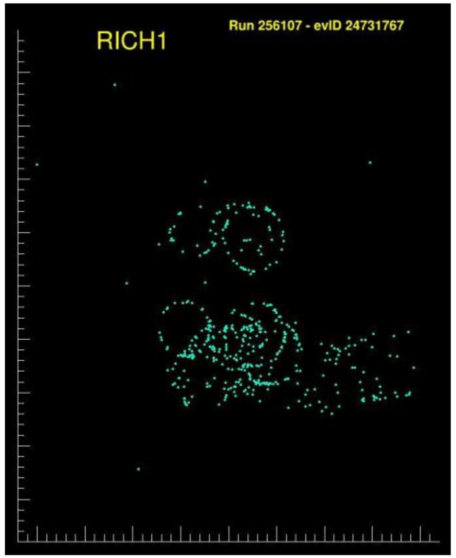
$$\cos\theta = \frac{c}{nv}$$

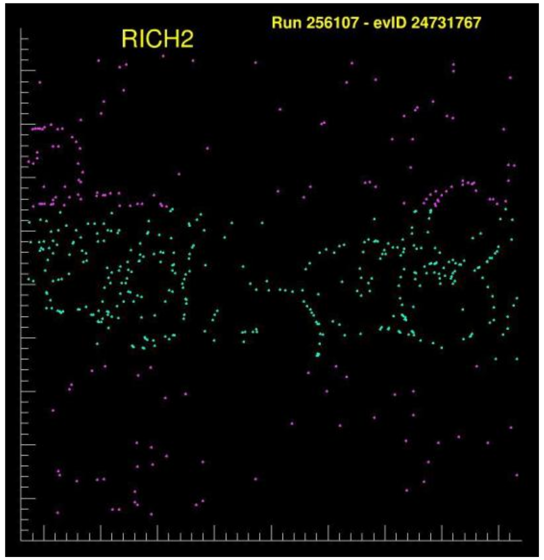
- In 3 dimensions the **Cherenkov light form a cone** as the particle continues to travel.
- If we make the volume with this medium short enough and collect the Cherenkov light on a plane, the cone is seen as a ring.
  - **The diameter of the ring then tells us the angle.**

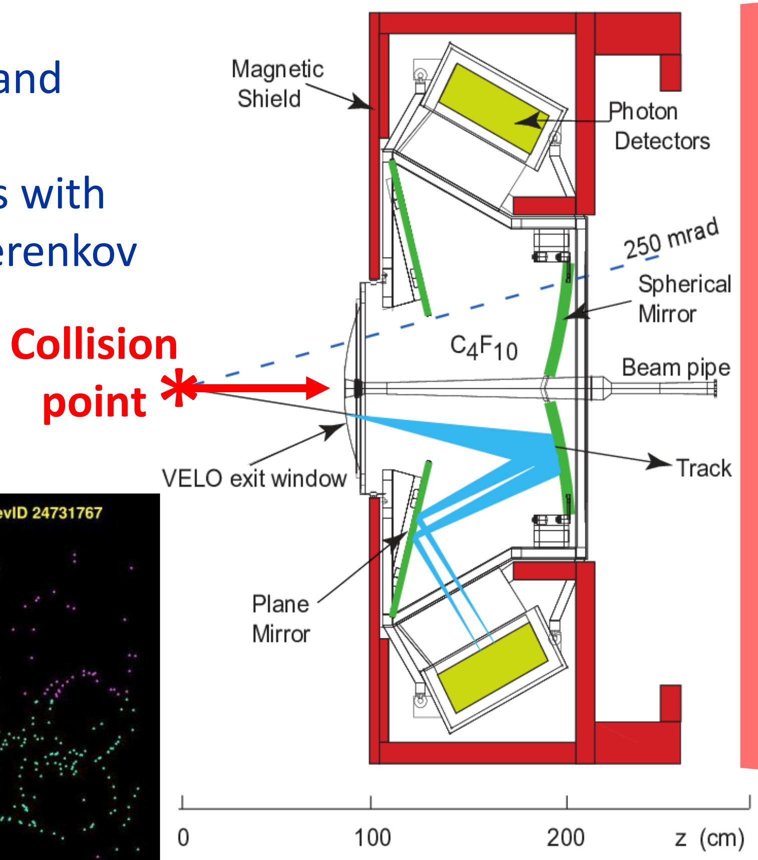




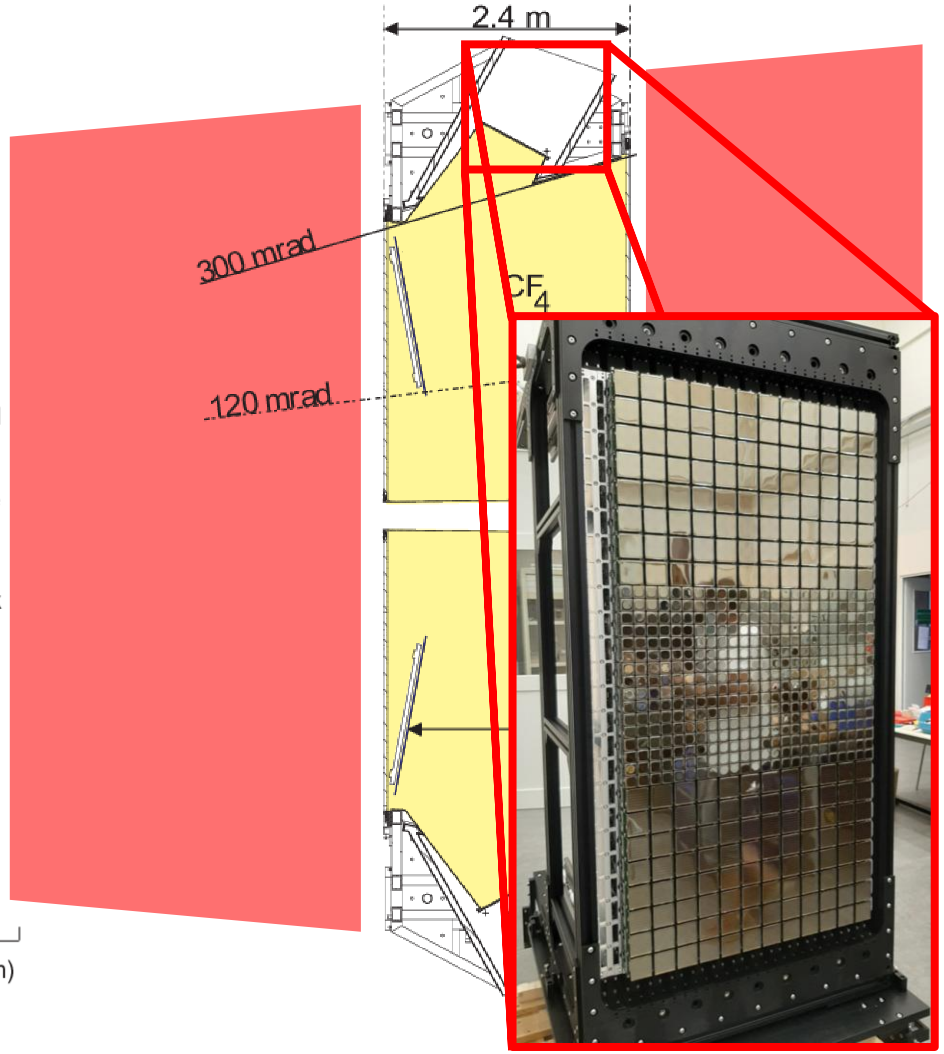
- **LHCb use Ring Imaging Cherenkov (RICH) detectors** to reliably identify pions from kaons.
  - Its important to tell them apart for the decays being studied!
- **LHCb has two RICH detectors**, before and after the magnet.
  - Both use MultiAnode PMTs (PMTs with many channels) to detect the Cherenkov light.
  - We need two to look at a larger momentum range!





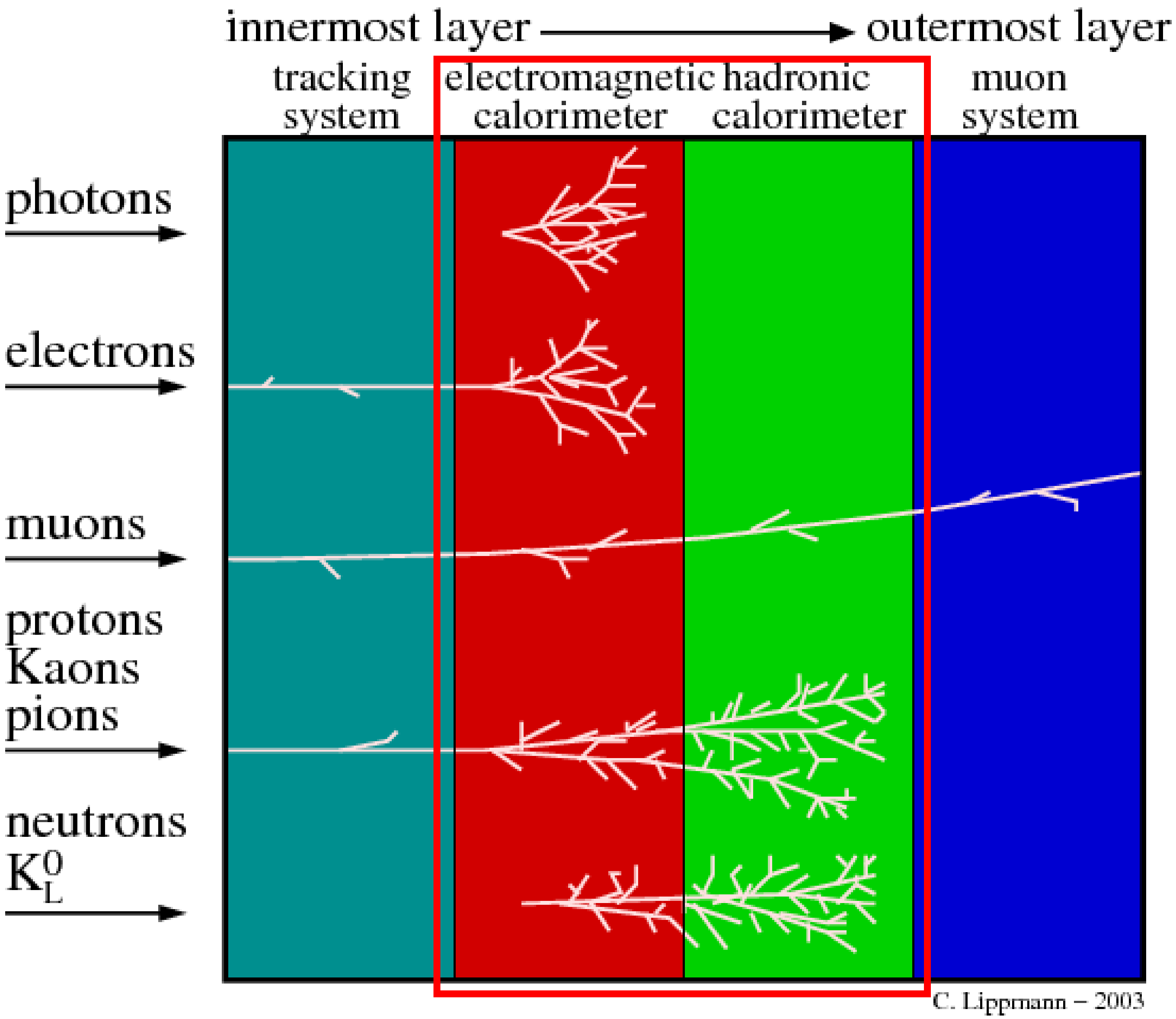


RICH1



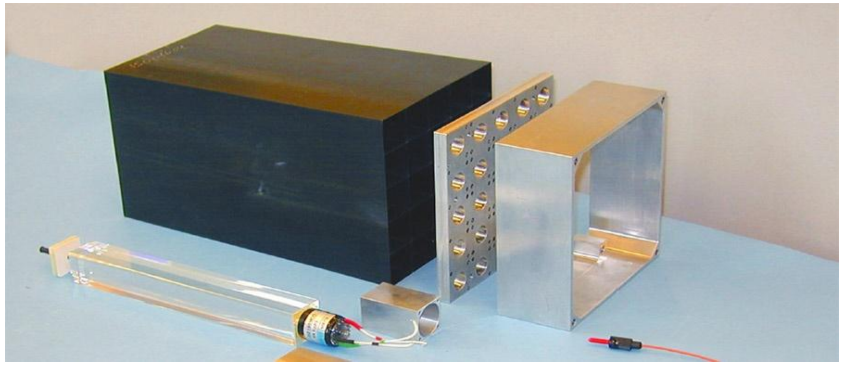
RICH2

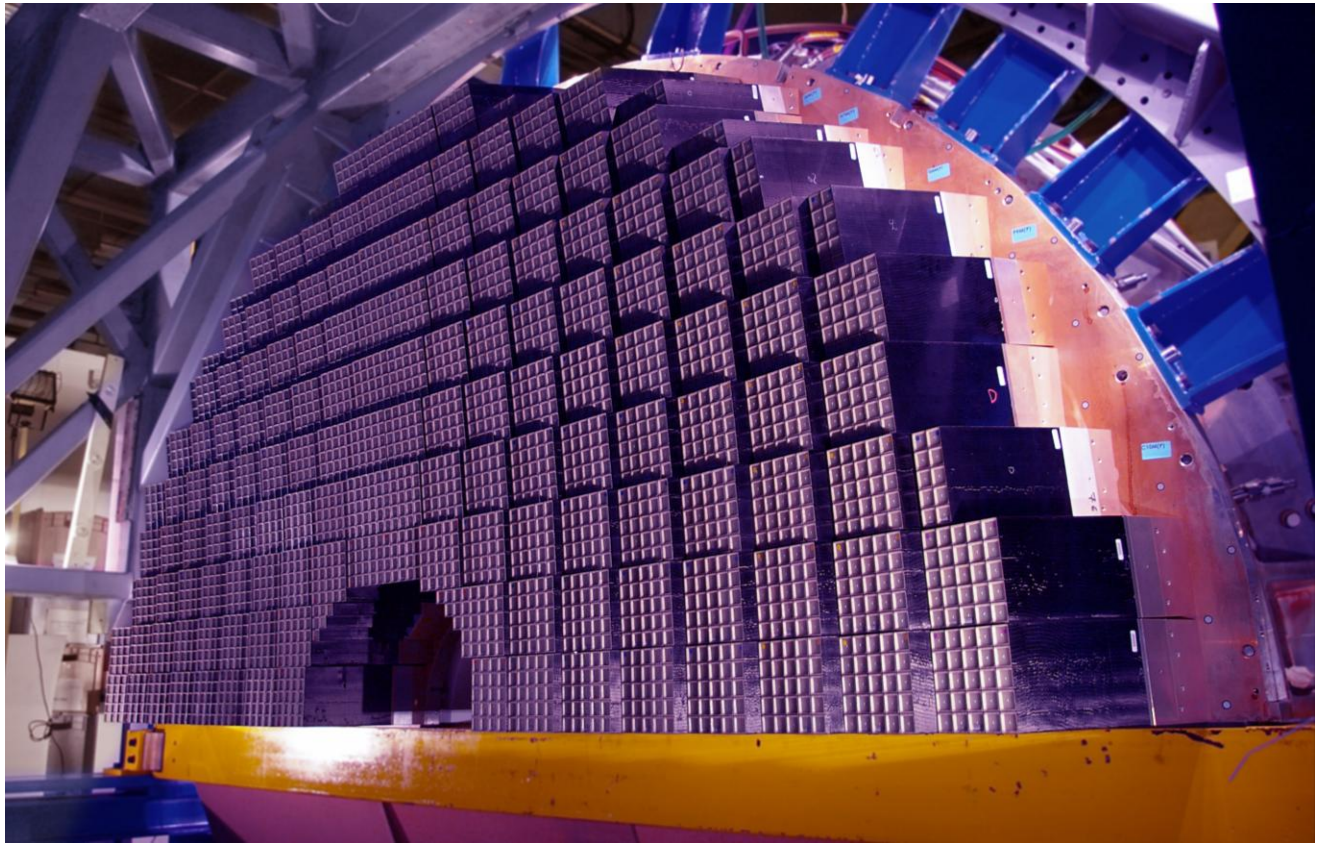
Typical Detector Layout



Homogeneous Calorimeters

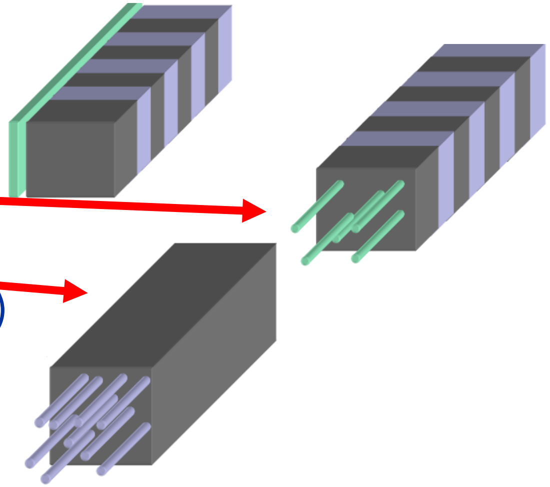
- In **homogeneous calorimeters** one material is used to produce a shower and measure the energy deposited in that cell.
  - Normally a high density, transparent material to scintillate or produce Cherenkov light.
- **The amount of light generated in the crystal will scale with the energy deposited.**
  - Very good energy resolution.
  - Very expensive.
  - Limited spatial resolution (dependant on cell size).
- CMS ECAL uses 80,000 $PbWO_4$ crystals!

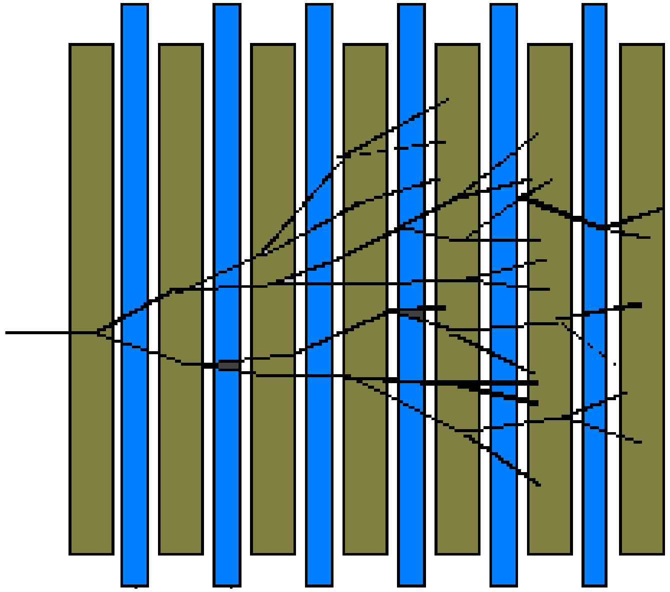


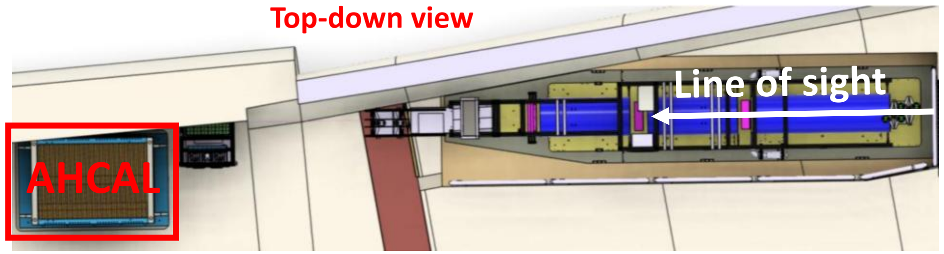


Sampling Calorimeter

- A sampling calorimeter has repeated layers of an active material and a passive material.
  - Active layers are typically a plastic scintillator.
  - Passive layers are dense, e.g. iron, tungsten, copper.
- There are several ways to readout sampling calorimeters:
  - Sandwich
  - Shaslik
  - Spaghetti
- An example is the Analogue Hadronic Calorimeter(AHCAL) prototype.
  - 40 layers of plastic scintillator and iron.
  - Readout by SiPMs.
  - Installed behind the FASER experiment this January.







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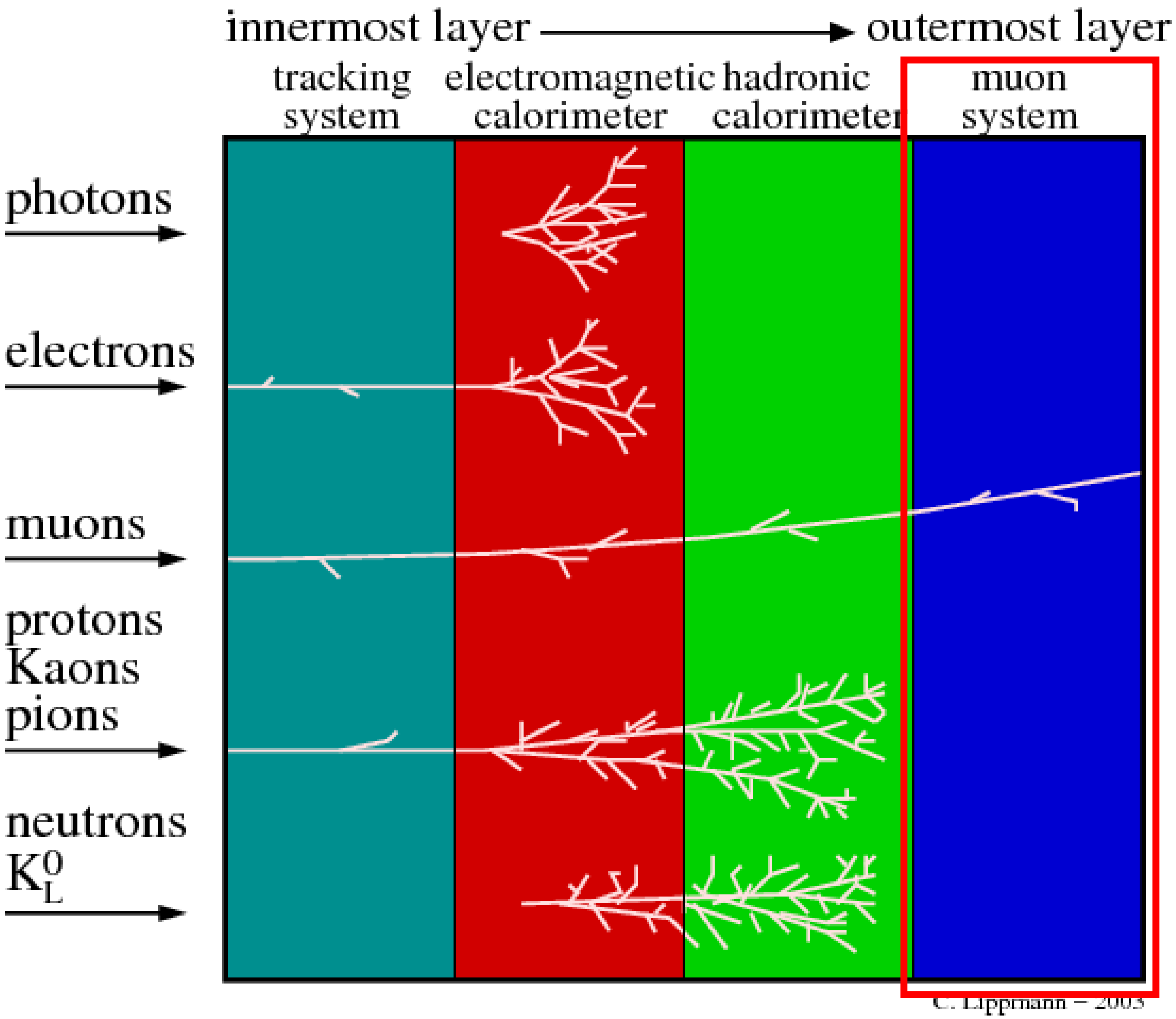
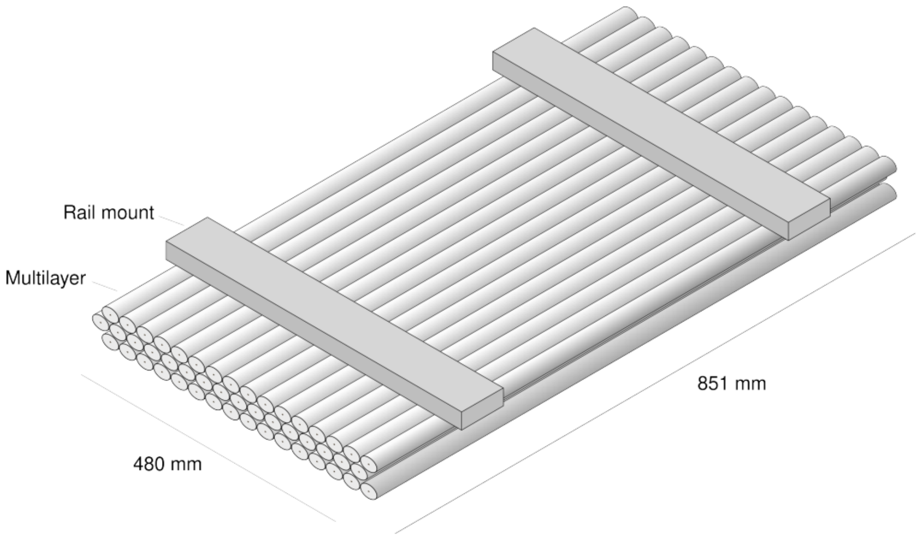
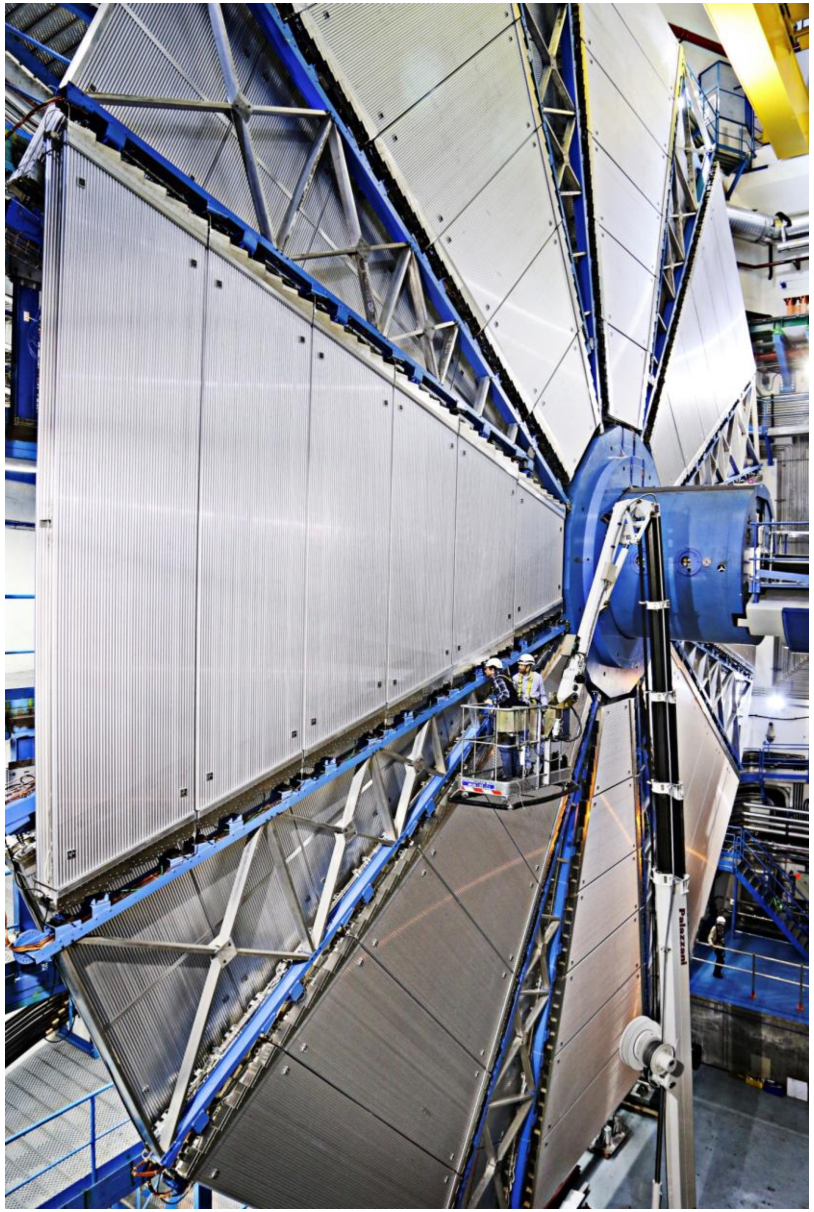


ATLAS Monitored Drift Tubes

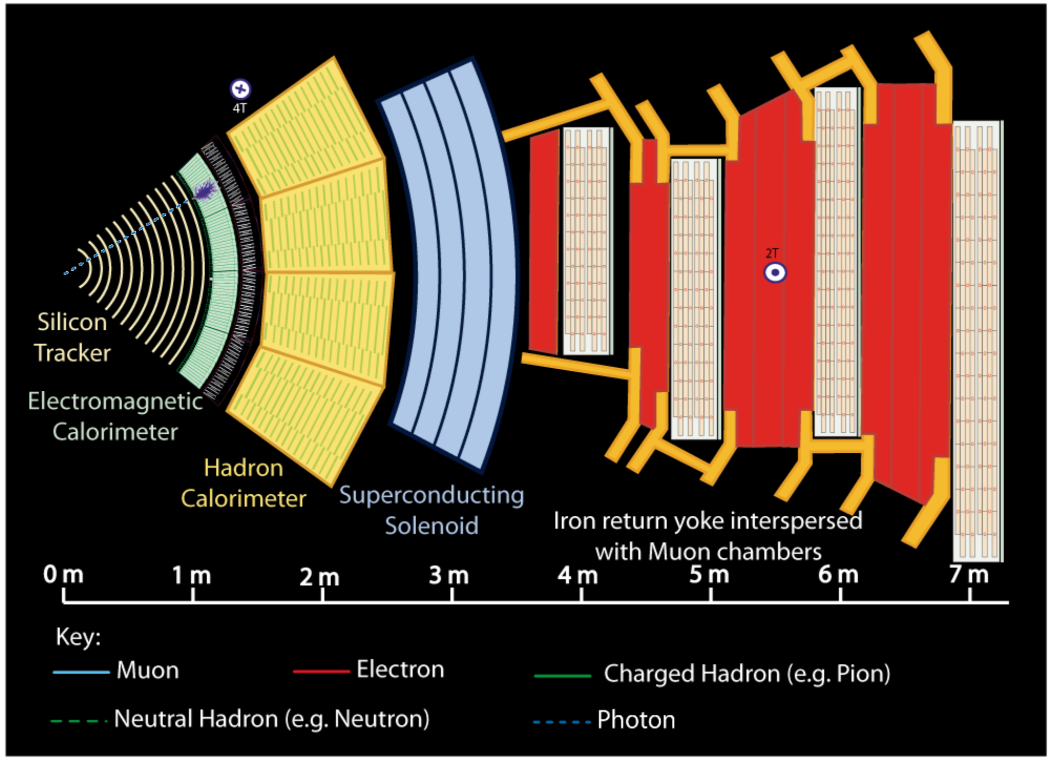
- **Muon Stations** are the last layers of detectors.
- **ATLAS** has 5 different technologies used for their muon spectrometer.
    - **Monitored Drift Tubes (MDTs)** are aluminium tubes with a wire running through the center.
- A muon passing through will ionise the gas mixture of argon (93 %) - CO_2 (7 %) @ 3 bar and start an avalanche.
    - The position of the muon is determined by using many layers of detectors.
    - The resulting special resolution is 60 µm
    - There are 354,000 drift tubes used.

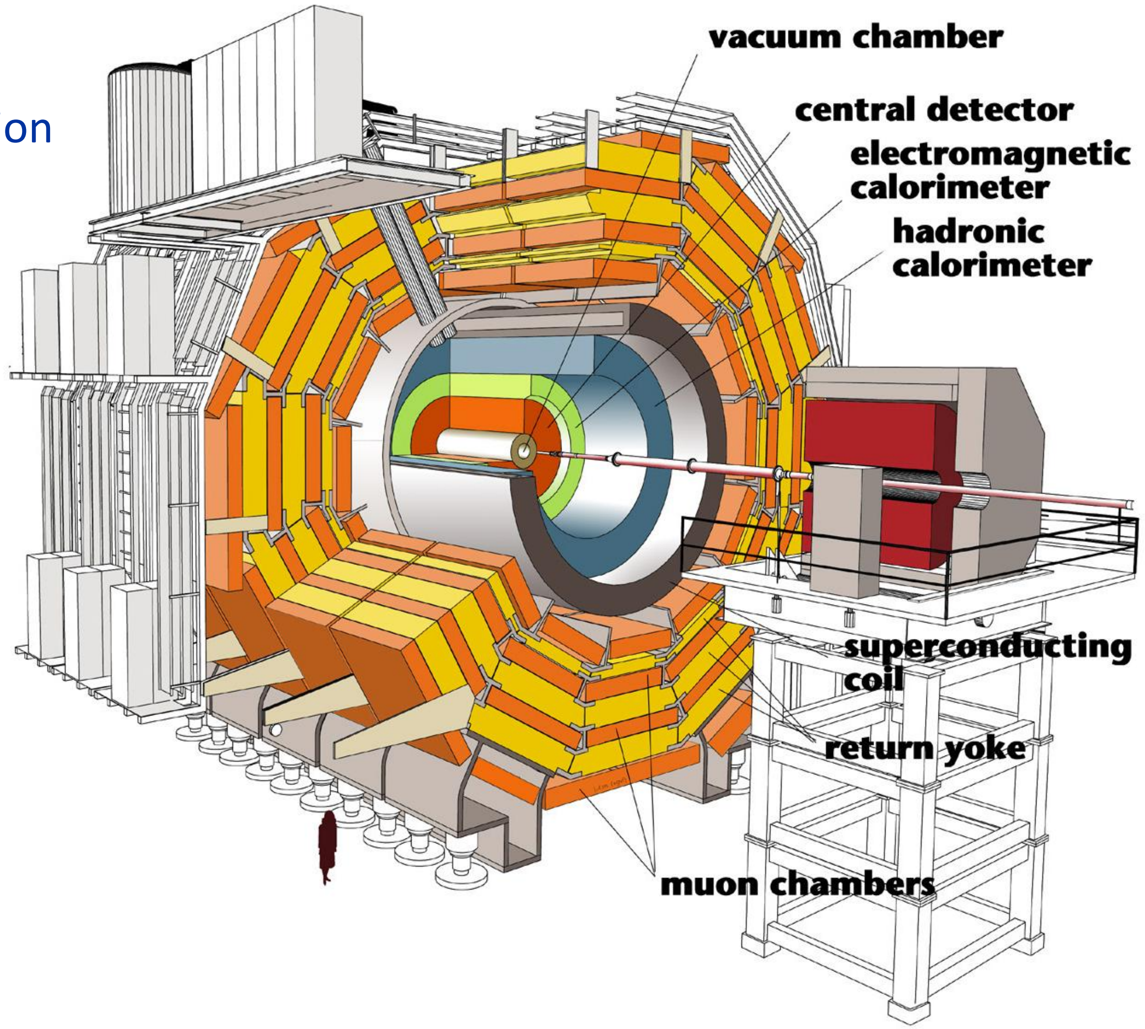




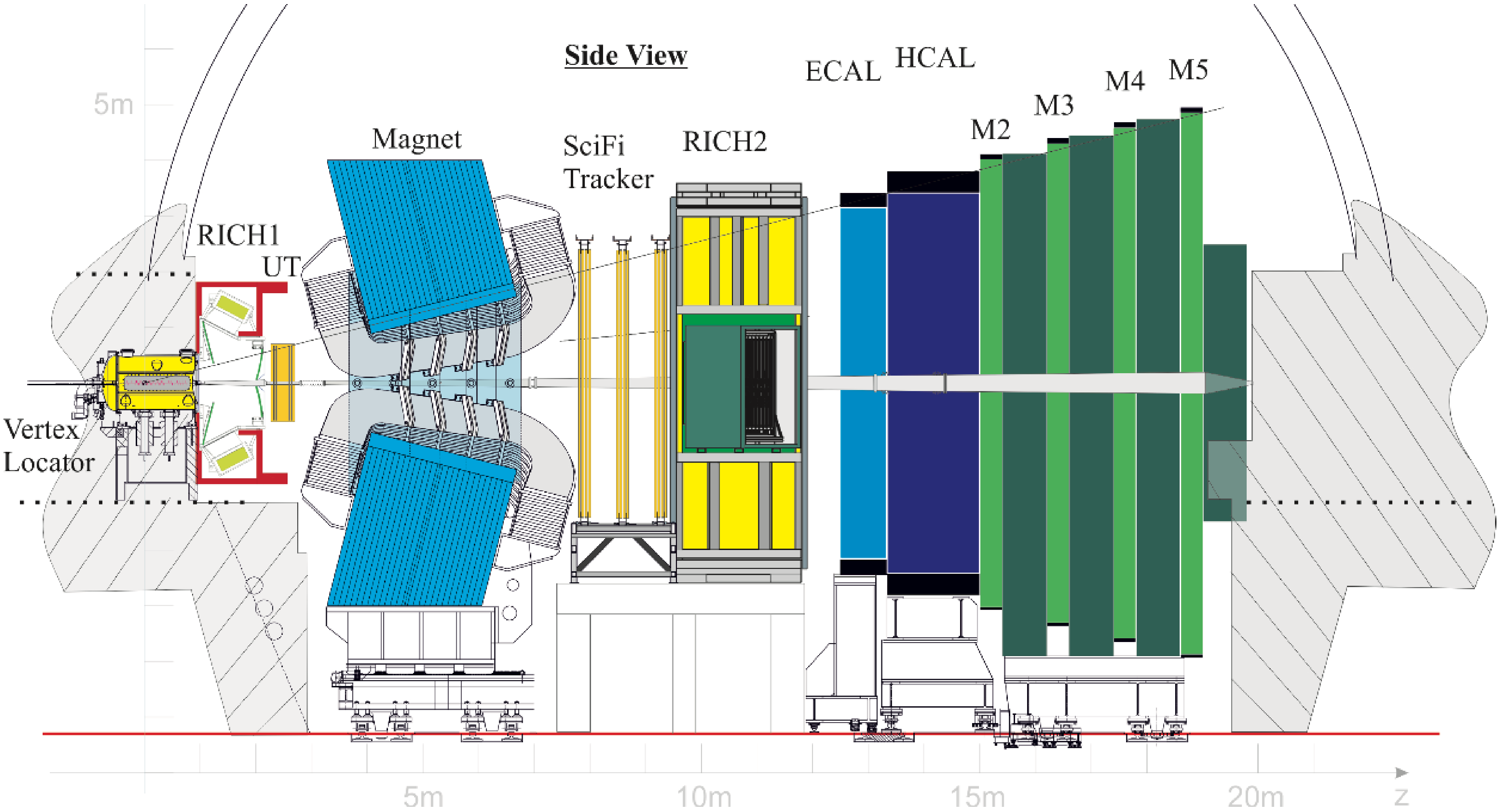
General Purpose Detector Systems

- General purpose detectors at the LHC.
  - Not necessarily designed to look at an individual decay.
- "Onion detectors"
  - Detectors in layers around the beam pipe with the interation point in the center.
  - End Caps on either end to cover all dimensions with detectors.





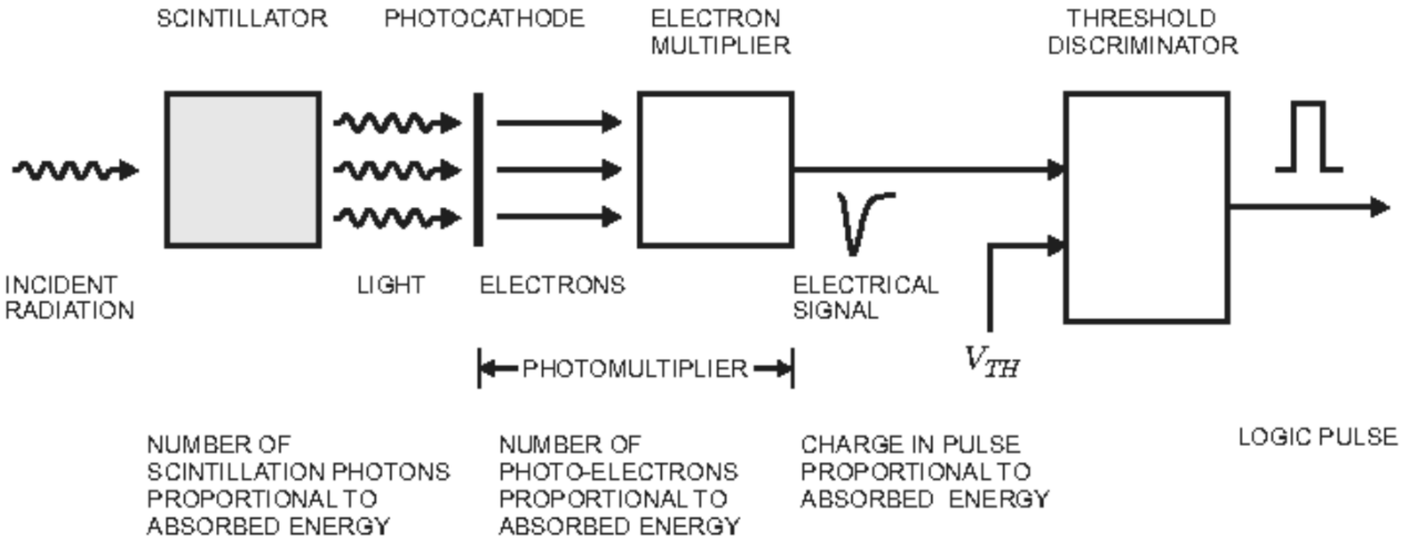
LHCb Experiment



Readout Electronics and Trigger

- **Front-end electronics** are the readout electronics that are connected to the detector.
  - FE electronics are used to manipulate the signal from the detector to be usable for the analysis.
    - This could involve amplifying a signal if the pulse from the detector is short.
    - As seen, some detectors like PMTs sort this out before reaching the readout.
  - FE electronics also digitise a signal if it is an analogue signal.

- But how do we know when to readout our detector?
  - LHCb for example triggers on when the protons collide.
  - But sometimes we only want to readout our detector when we have something interesting (for example) two detectors see a particle at the same time.
    - A coincidence trigger.



Detector Operations

Thank You For Listening