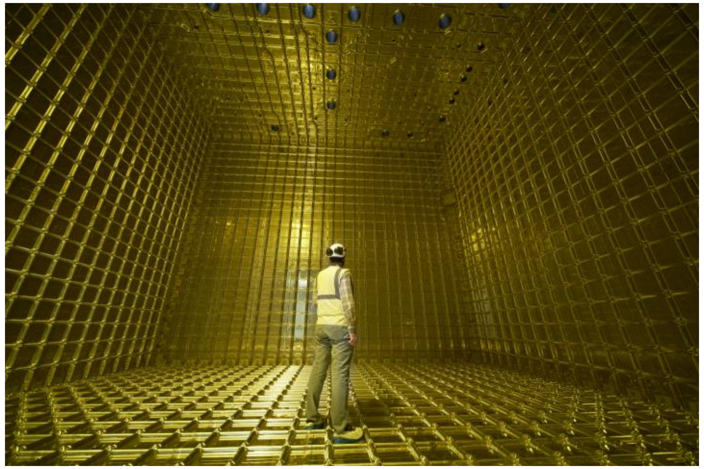
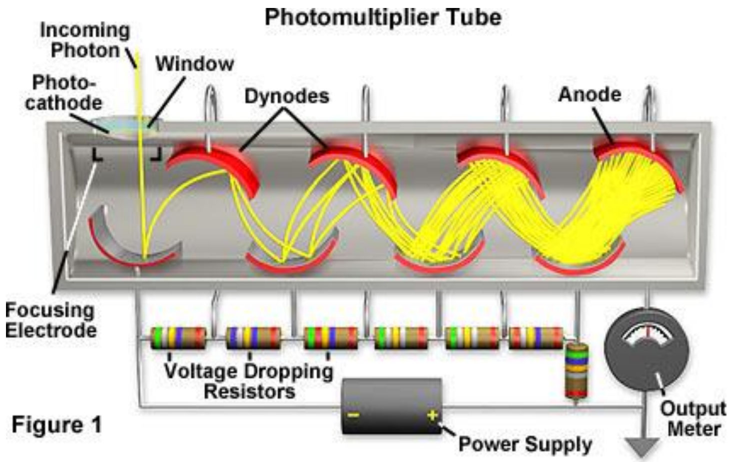
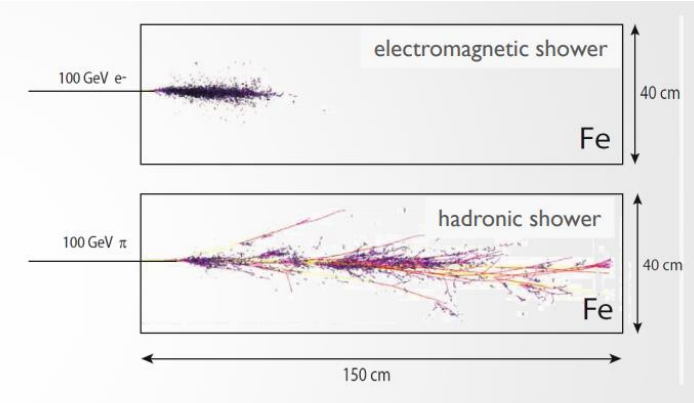
Particle Detection

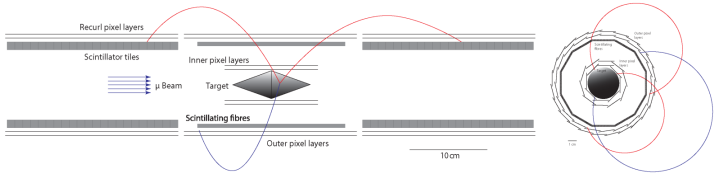
Liverpool@CERN
Particle Physics School
2024

Ned Howarth



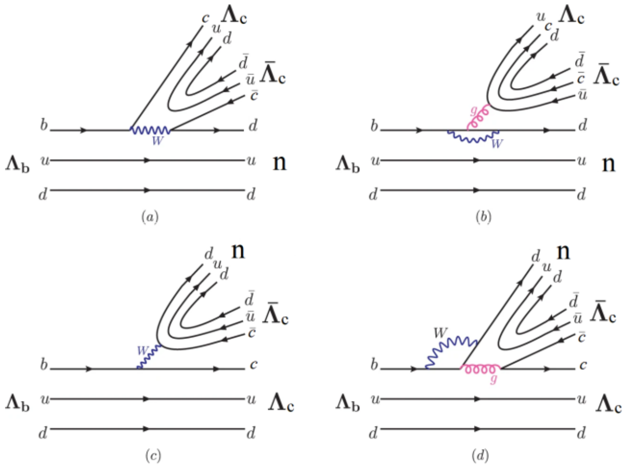






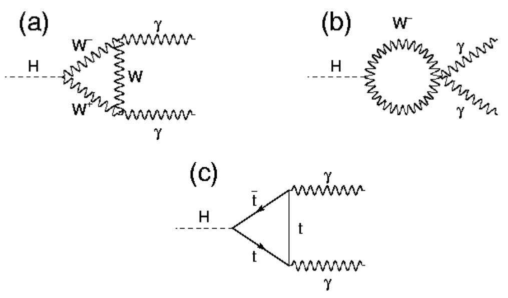
About Me

- Born and raised in south London.
- Undergrad/Mphys in Edinburgh.
- Started PhD at the university of Liverpool in October 2022.
- Have been based at CERN for my second year of PhD.
- Researcher on LHCb Looking at purely baryonic decays and neutrons.



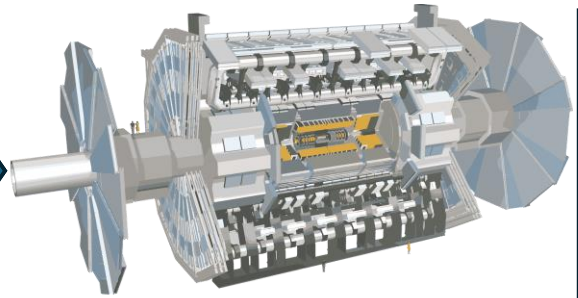
Testing The SM

- We have a model that predicts how particles behave.
- We know it is incomplete so we need to probe it as best we can.
- How do we get from theory to result in particle physics?

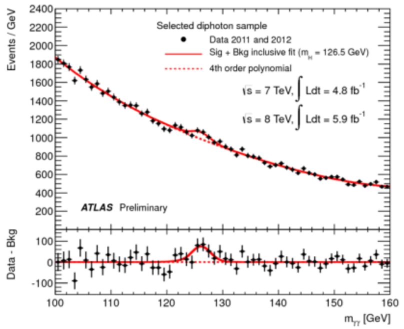


$$\begin{aligned}\mathscr{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\psi}\not{D}\psi + h.c. \\ &+ \bar{\psi}_i y_{ij}\psi_j\phi + h.c. \\ &+ |D_\mu\phi|^2 - V(\phi)\end{aligned}$$

- Physics Processes
- Interaction with matter.

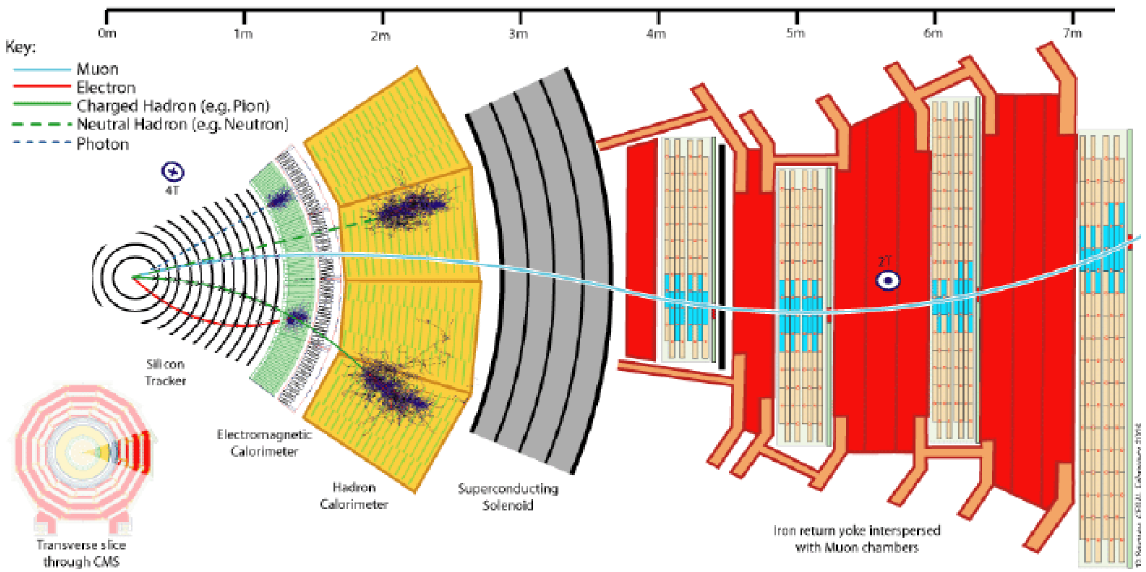


- Digitisation
- Particle Signatures
- Data Analysis



What can we See?

- What do we mean by “seen in the detector”?
- E.g At the LHC we cannot observe particle processes in real time by eye.
- Through interactions with matter the particles leave behind footprints/ signatures that we can use to deduce what happened



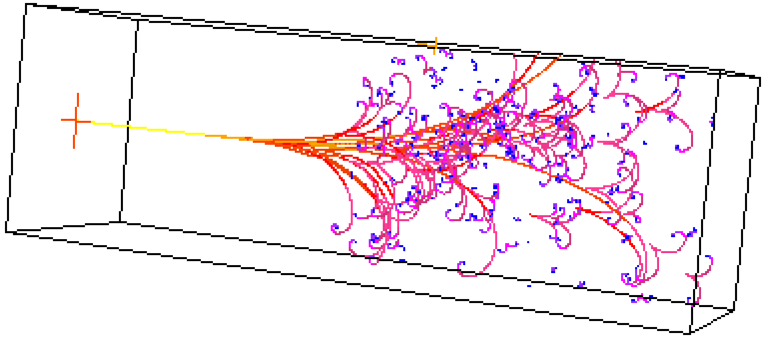
Detector

Physicist

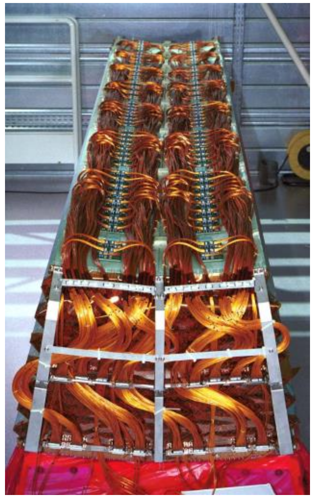
Interactions with Matter; Our Toolkit.

- Particle enters some material.
- What happens?
- How can we utilise that to build a detector.
- Can we optimise to look for certain physics.
- Let's build up a toolkit.

Interaction

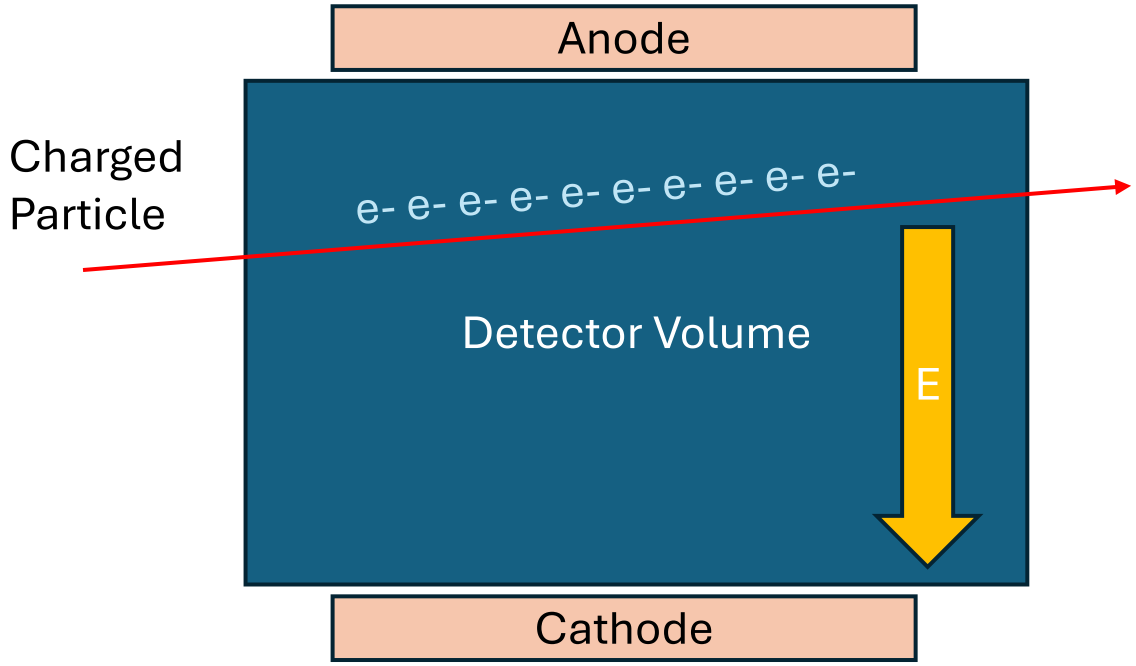


Example Detector



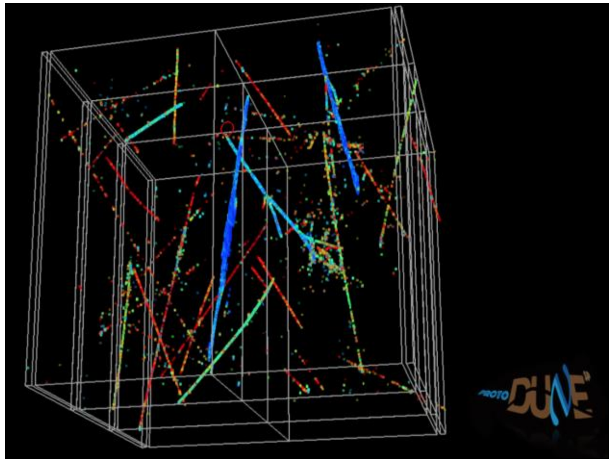
Ionisation in Material

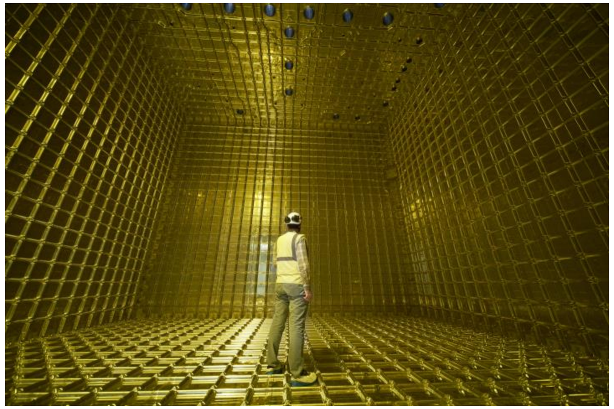
- Did a charged particle pass through our detector material.
- If we pick the right material, we can ionise it by exciting the detector volume along the particle path.
- Free electrons are produced.
- We can cause the free charge to drift using an electric field.
- Collecting our charge allows us to reconstruct the particle track.
- We have a time projection chamber.

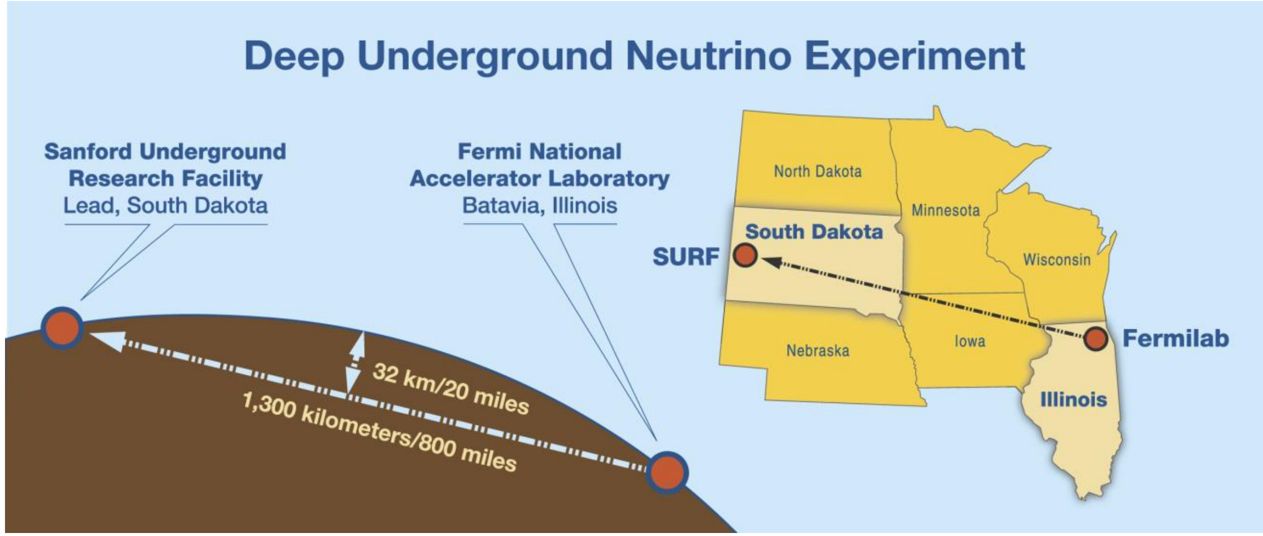


Time Projection Chambers - Dune

- There are now many different TPCs that use different material interactions to create free charge that they can measure.
- Dune is a large-scale neutrino experiment that is currently being built in South Dakota.
- It will be filled with a huge! volume of liquid argon.
- When a neutrino bumps into an argon atom's core, it produces particles that knock loose electrons in the liquid argon.
- Proto Dune is based at CERN.

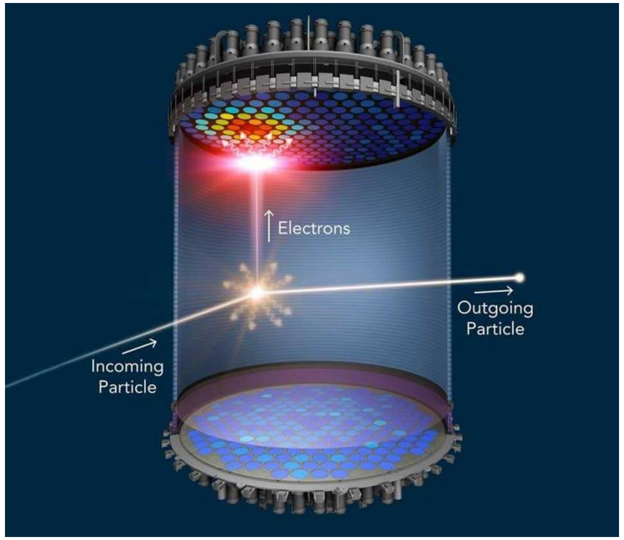






Time Projection Chambers – Dark Matter

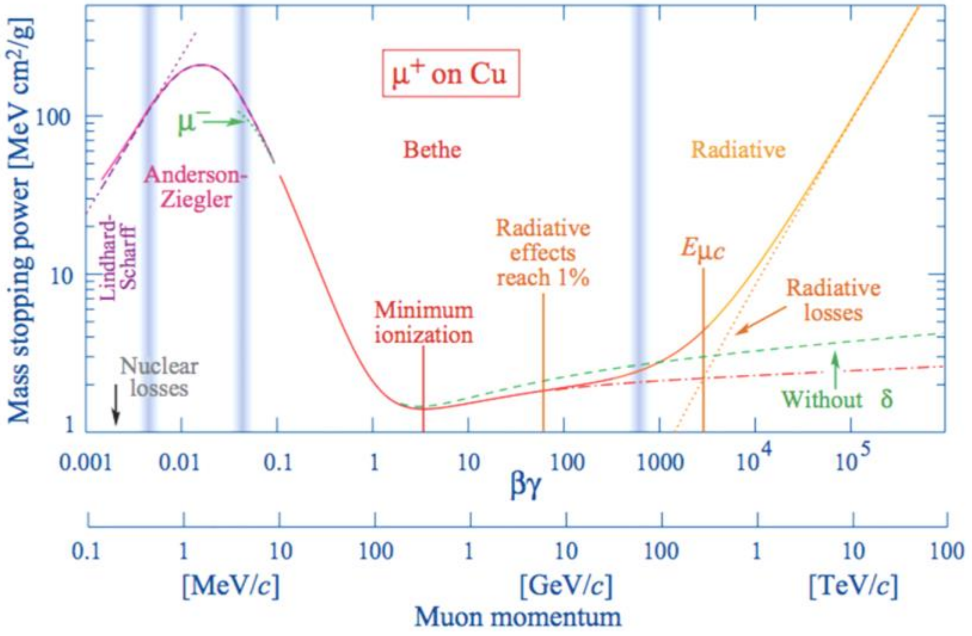
- Dark Matter Physicists are looking for dark matter particle candidates called WIMPs, weakly interacting massive particles.
- This through ionisation by nuclear recoil.
- One DM TPC Experiment is Lux Zeppelin.
- Detector medium is liquid xenon.
- Also in a mine in south Dakota…



Bethe-Bloch Equation

- Instead of particles passing through a medium can we stop them.
- Is there a general formula for relativistic particles in heavy material?
- We can use the Bethe-Bloch Equation:

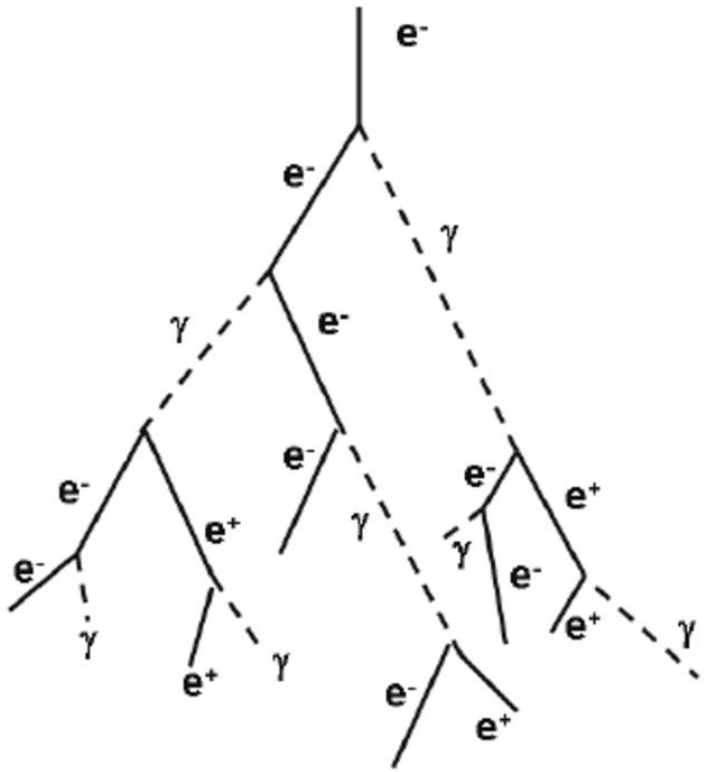
$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 NZ}{(4\pi\varepsilon_0)^2 M_e v^2}\left[\ln\left(\frac{2M_e v^2}{I}\right) - \ln(1-\beta^2) - \beta^2\right]$$



- Z atomic number
- I is the average energy required to ionize the medium
- Bethe-treatment is accurate to 1% down to $\boldsymbol{\beta}\approx 0.05$, below that there is no accurate theory. Even further below, non-ionizing nuclear recoils dominate.
- At ultra-relativistic energies, radiative losses become important.

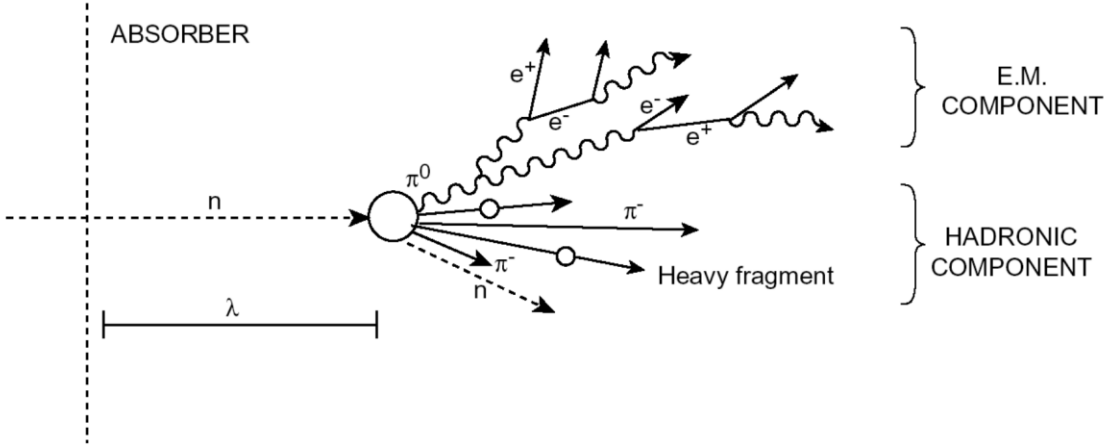
Electromagnetic Showers

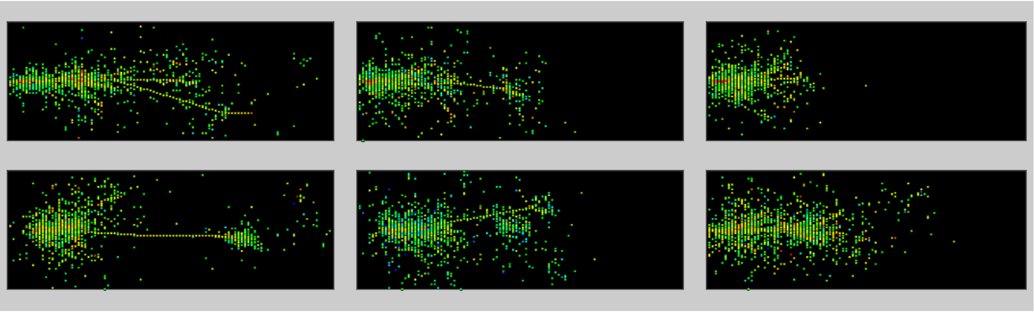
- An electromagnetic shower begins when a high-energy electron, positron or photon enters a material.
- Photons interact via pair production -> e+ e-.
- Electrons and positrons interact via Bremsstrahlung.
- Bremsstrahlung is the emission of photons produced by the deceleration of an electron when deflected by atomic nuclei.
- leads to a cascade of particles of decreasing energy until photons fall below the pair production threshold.

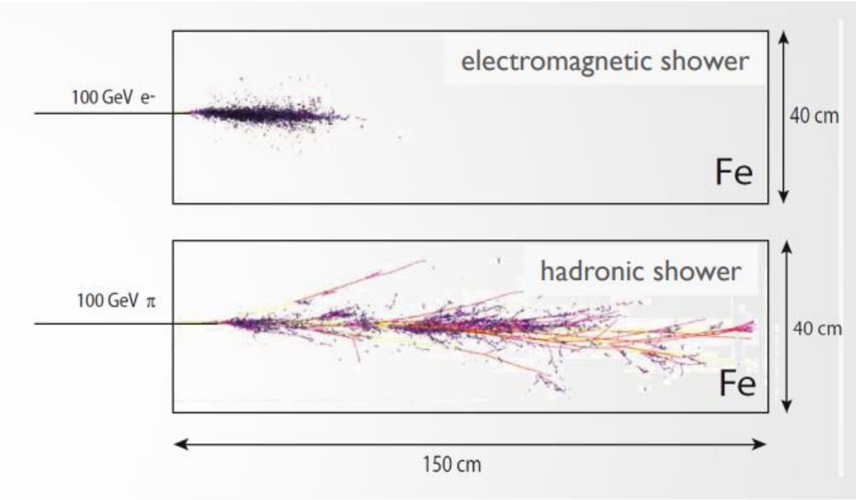


Hadronic Showers

- Hadronic showers are initiated by the hard collision of an incident hadron with a nucleus.
- Neutral pions decay into 2 photons and begin EM Showers.
- Typically more difficult to understand the geometry of than EM Showers.
- Need more material capture the full shower.

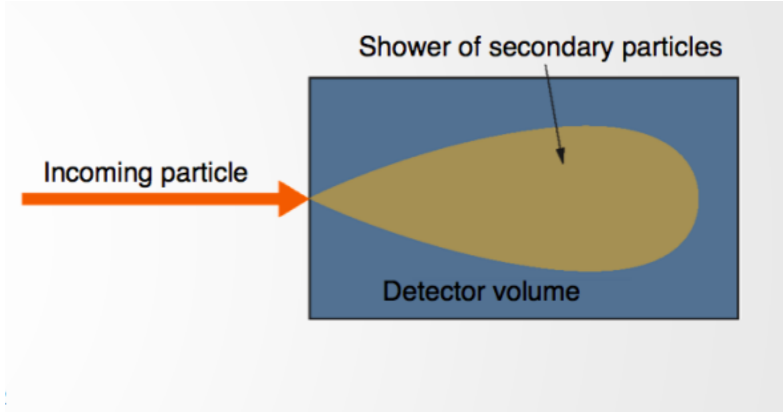


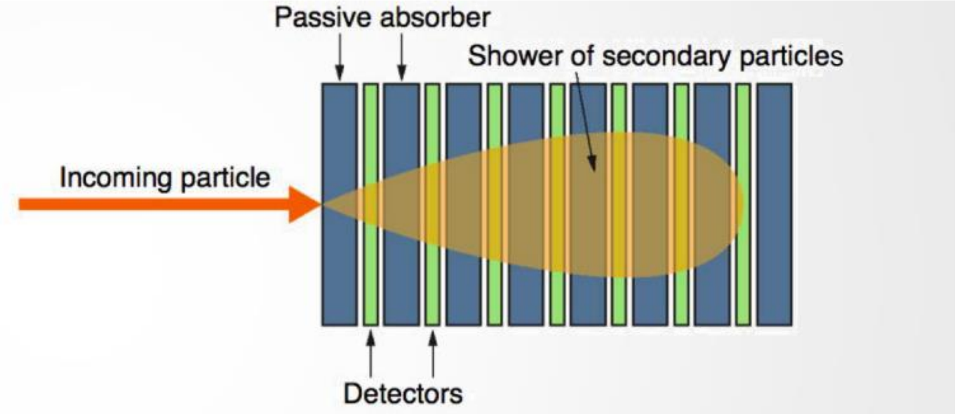




Calorimetry

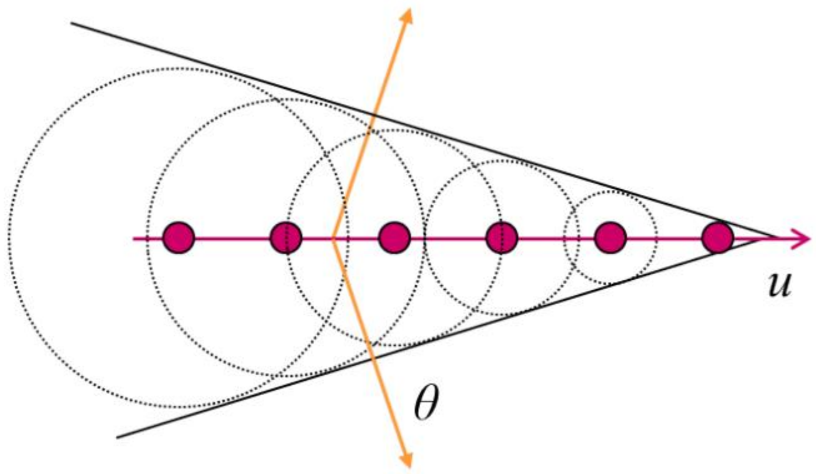
- Once you have a shower you need to measure It.
- Calorimeters are either Homogeneous or sampling.
- Homogeneous Calorimeters: absorbing material is also the sampling material.
- Sampling Calorimeters: Absorbing material and sampling material are layered.
- Sampling Material e.g Plastic or crystal scintillators, liquid noble gas ionization chambers.
- EM and Hadronic calorimetry used in all General-purpose collider detectors.





The Cherenkov Effect

- What happens when we exceed the speed of light…
- In a medium.
- A particle will release Cherenkov radiations in the form of a cone of photons



The Cherenkov Effect

- Can we measure it?
- Measure light with Photomultiplier tubes (PMTs).
- Take an incoming photon and multiply its signal with a series of increased voltages.
- Sometimes LOTs like at Super Kamiokande in Japan.

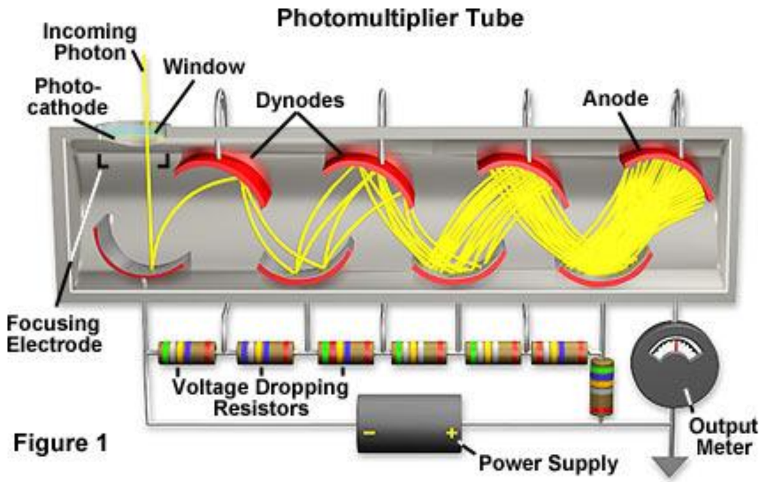
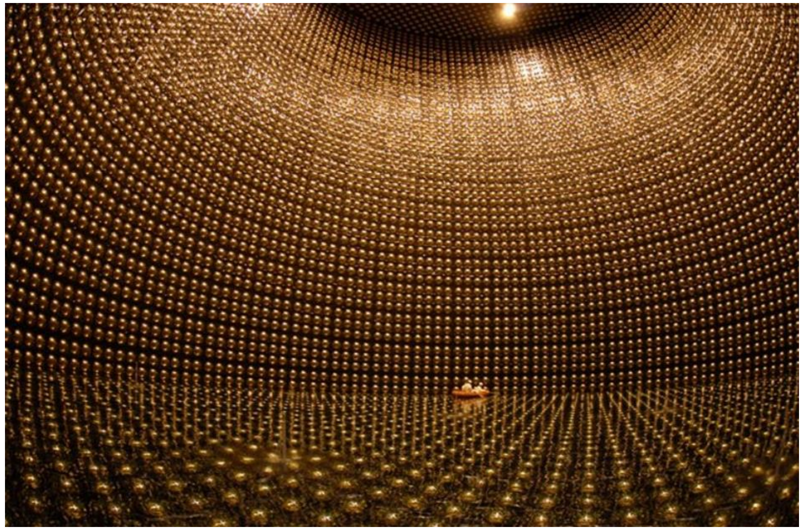
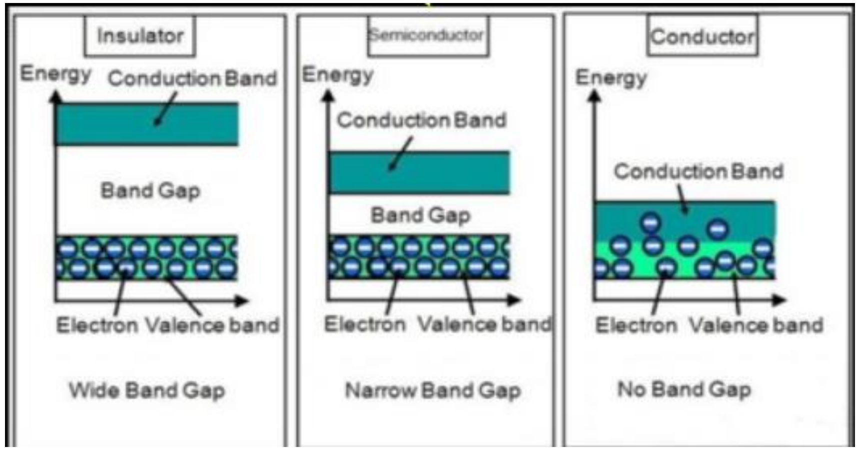


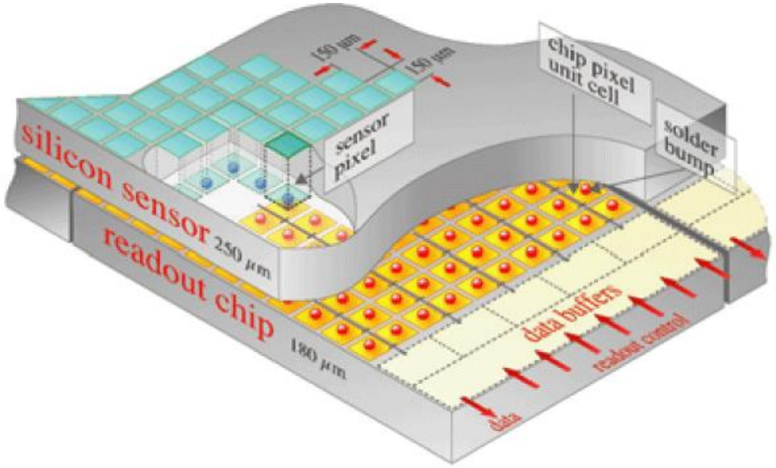
Figure 1

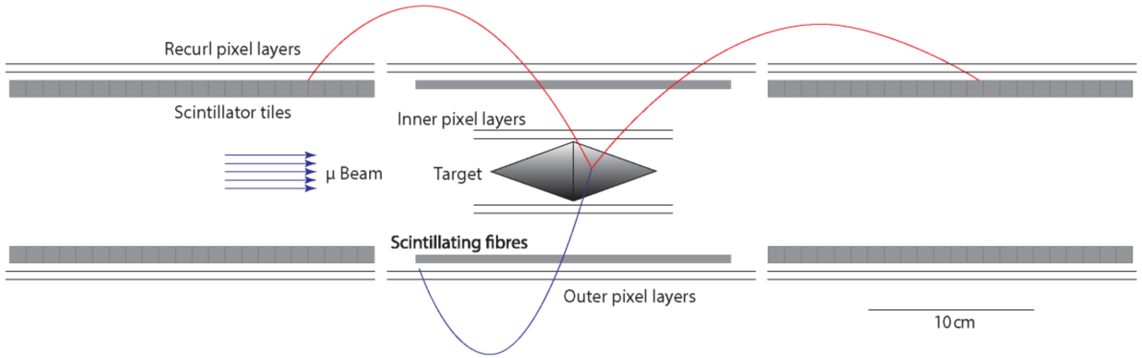


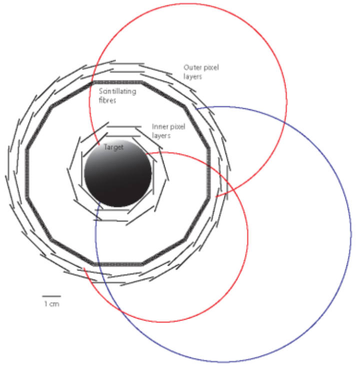
Silicon Tracking

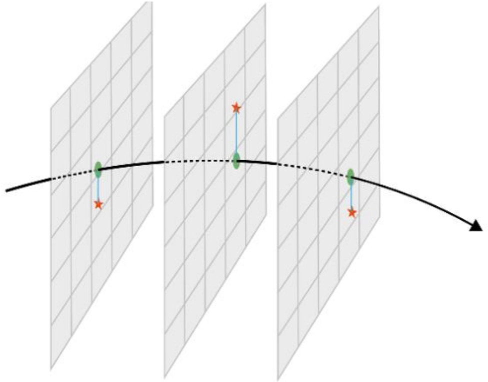
- Charged particles collide with silicon atoms, liberating electrons and creating an electric current.
- Semiconductor: Low energy across band gap.
- High mobility, fast charge collection.
- Usually set out an array of silicon pixels to map charged particle tracks.
- Bend charged particles through magnetic field to get their momentum.
- Used in loads of Collider experiments and fixed target experiments like Mu3e.





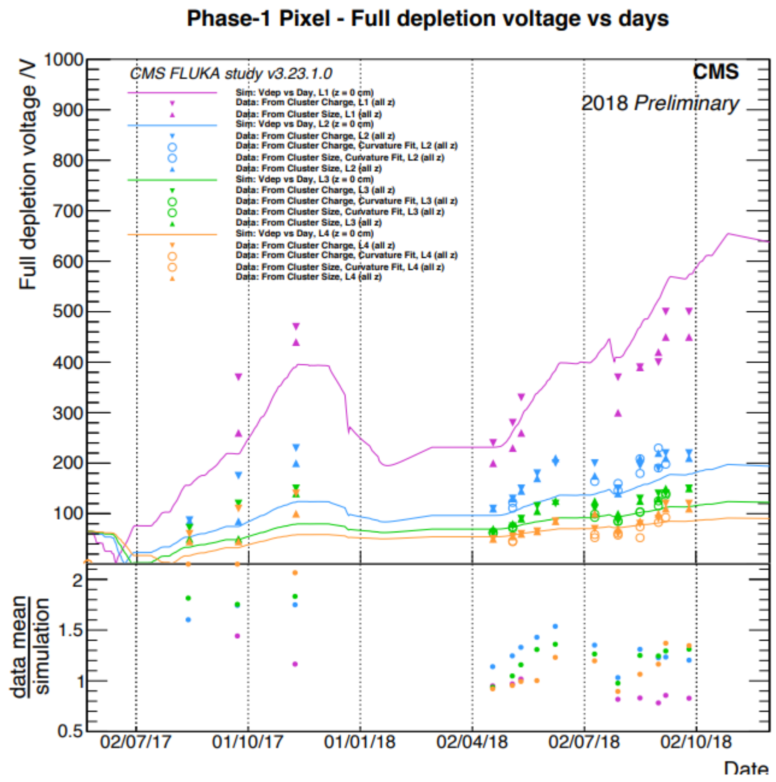


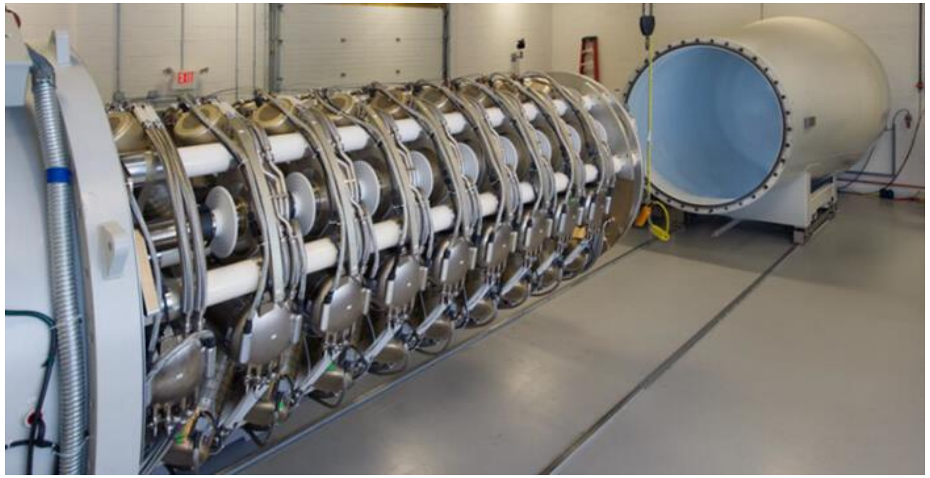




Radiation Hardness

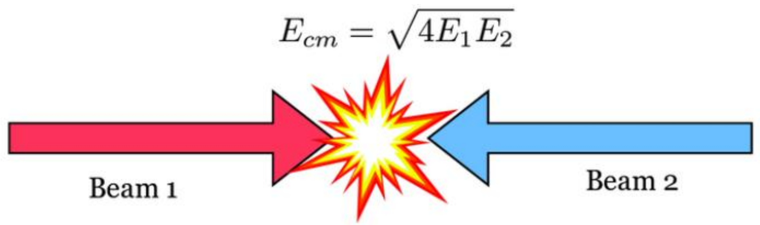
- We want our detectors to last a long time.
- How do they hold up with all the ionisation radiation?
- Electrical and detector components will deteriorate over time.
- Silicon chips are susceptible, and pixels sometimes suffer from drop out.
- We are aware of this deterioration and make replacements when necessary.
- Components are sent off to smaller acceleration rings to be irradiated and tested for radiation ageing – Cyclotron at Birmingham.

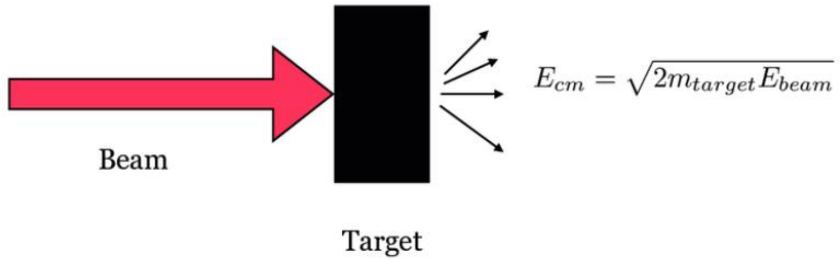


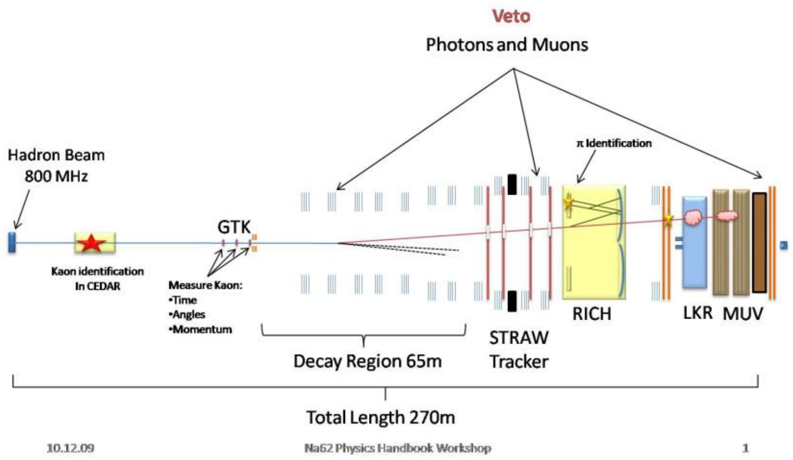


Fixed target Vs Collider

- What is a detectors purpose, is it specific or general.
- The LHC works at the energy frontier – this can only be reached with colliding bunches of particles head on.
- Fixed target has lower energies, but you can reach higher luminosities.
- More events means you can search for rarer decays.
- E.g Na62 an ultra-rare kaon decay experiment looking for decays of order 10e-12.







General Purpose at the LHC

- Example: slice of CMS detector.
- Not necessarily designed for specific decay.
- Hopefully, this image makes more sense than it did at the beginning.
- Thanks! Questions?