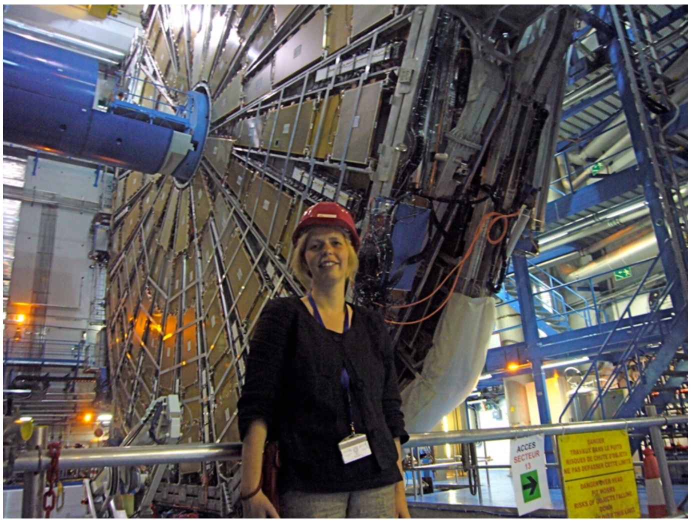
Subatomic Physics:

Particle Physics

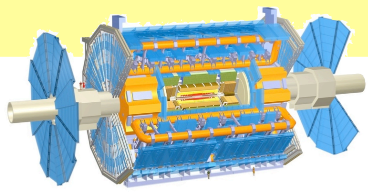
Lecture 5: Particle Detection with the ATLAS detector

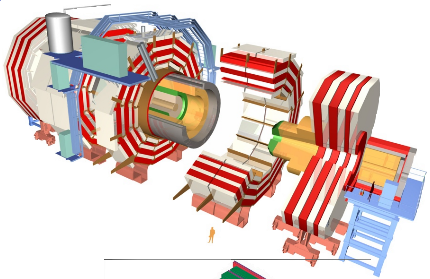
November 17th 2009

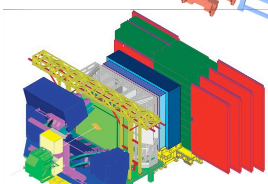


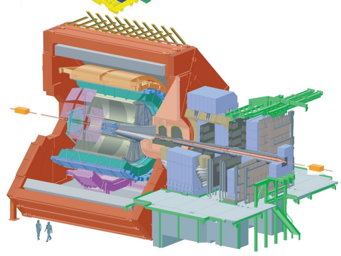
- **Particle Detectors:**
  - The ATLAS detector
  - Interactions of particles with matter
  - Particle reconstruction

Introduction







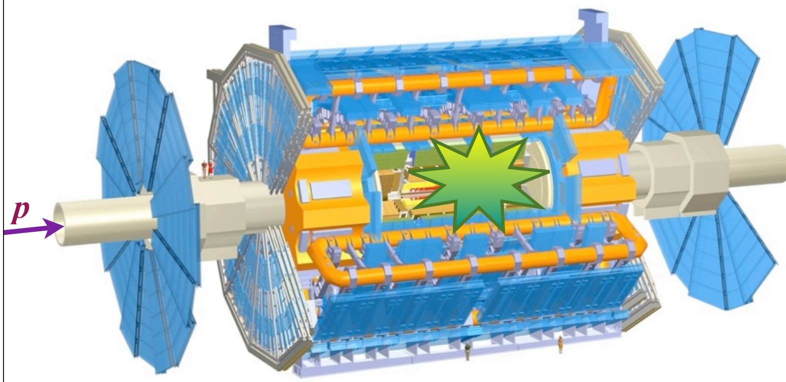


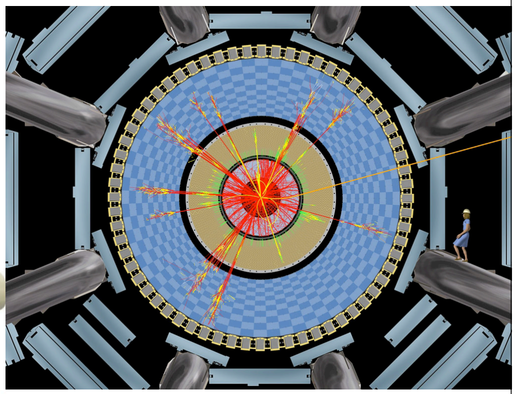
- Each of the four LHC collision point is surrounded by one of LHC experiments: ATLAS, CMS, LHCb, ALICE.
- The detector aims to detect all particles that live long enough to interact with the detector.
- For each final state particles try to measure:
  - Energy and momentum
  - Trajectory through the detector
  - Electric charge
  - Identity of particle (electron or photon or ...)
- Innermost part of detector is few centimetres from the interaction point.
- Recall: particles travel a distance $L=\beta\gamma c\tau$ before decaying, therefore particles with $\tau > \sim 10^{-10}$ s live long enough to hit detector
  - $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, K^0, p, n, \gamma, \nu$
- A series of different detection techniques is used to identify and these particles.
- Infer the existence of shorter-lived particles from the decay produces.

The ATLAS Detector

- Most general purpose collider detectors are conceptually similar
- ATLAS is a cylinder with a total length of 42 m and a radius of 11 m.

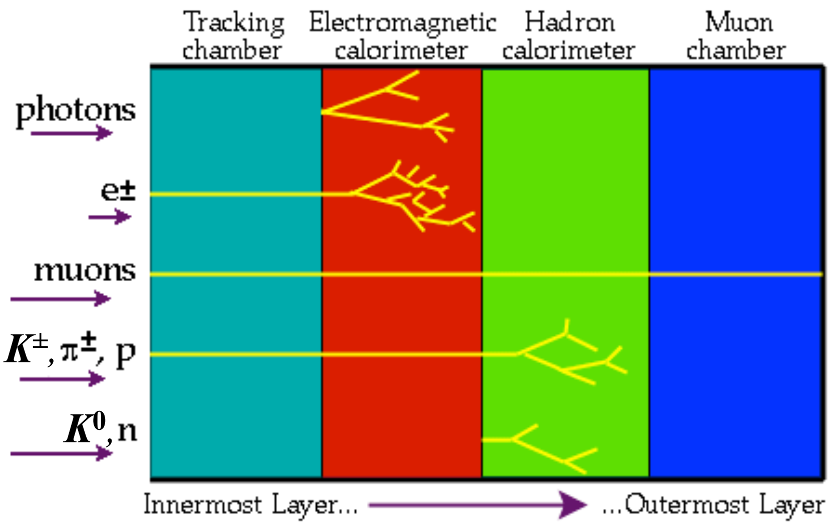
- From inside to out:
  1. Silicon pixel detector
  2. Tracking detector
  3. Electromagnetic Calorimeter
  4. 2 T Solenoid Magnet
  5. Hadronic calorimeter
  6. Muon detectors



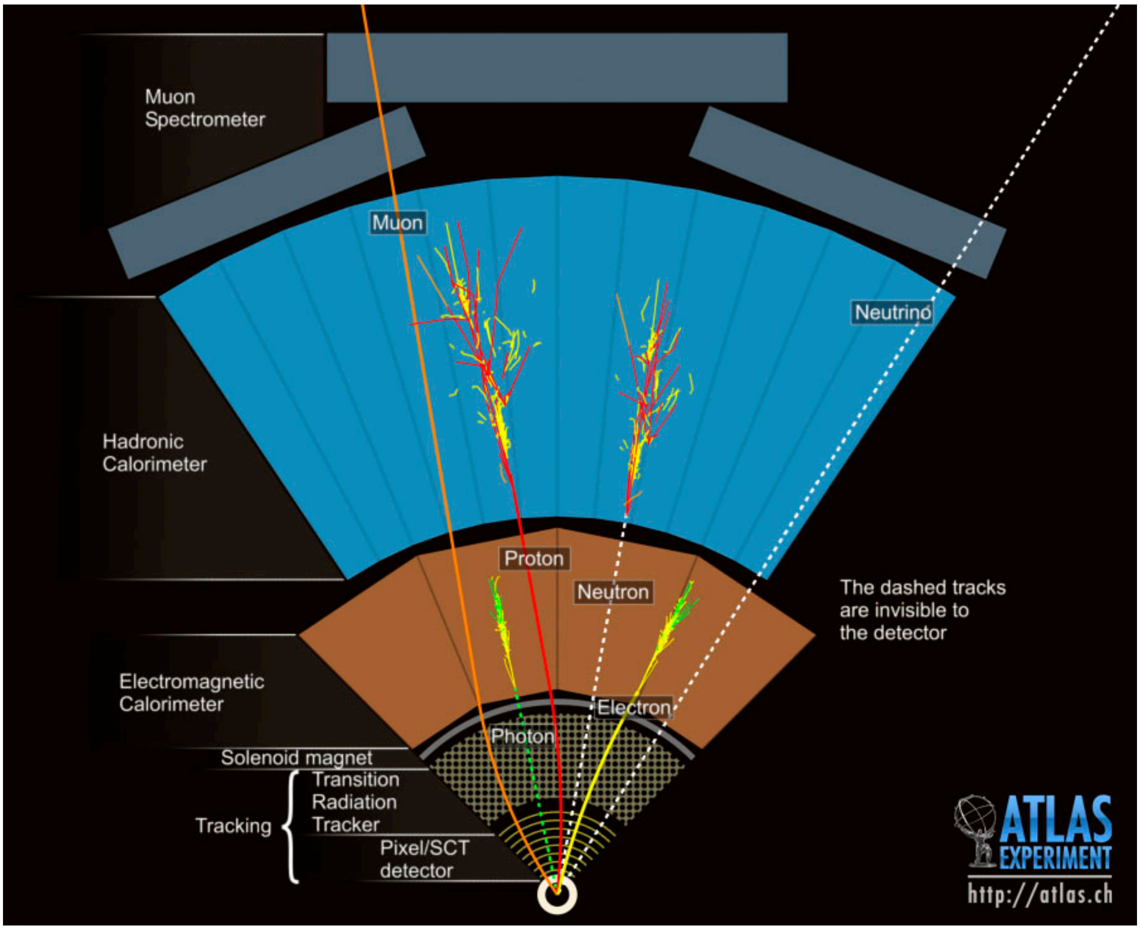


lots more at http://atlas.ch/

Interactions with Matter

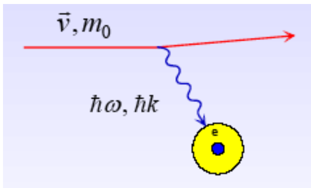


- Inner detector layers measures charged particle trajectory (and momentum $p_T[\mathrm{GeV}/c] = 0.3\,B[\mathrm{T}]\,\rho[\mathrm{m}]$) without interfering with particle too much
- Calorimeter layers measure energy by fully absorbing the particles (destructive measurement).
- Muons do not interact in calorimeter very much: final detection layer to detect muons.



Charged Particle Interactions

- Moving charged particles emit photon radiation.
- If there is other matter present, photon energy can be transferred and hence the charged particle looses energy.
- Energy loss of charged particle through matter is described by **Coulomb scattering**

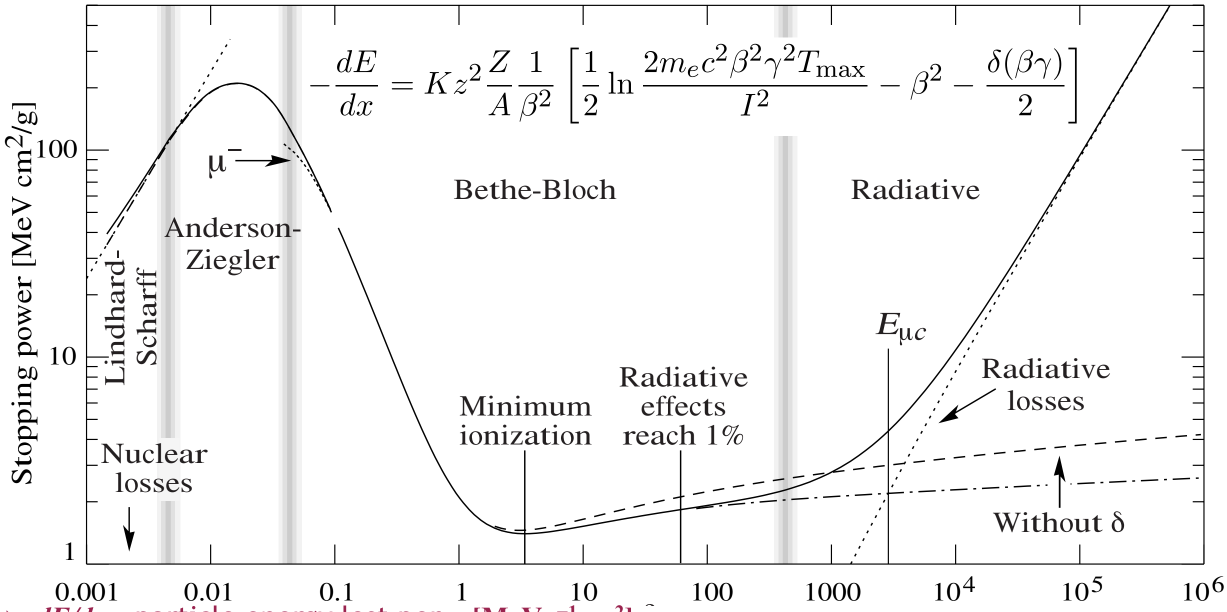


- A small amount of energy loss causes **ionisation**, e.g.:
  - ionisation of atoms in a gas
  - electron-hole creation in a solid state detector
- Use ionisation signal to identify space points where a charged particle has passed.
- Ionisation energy loss, dE/dx, is given by **Bethe-Bloch** formula (on following slides).

- If the detection medium is dense the charged particle may eventually deposit all of its energy in the detector: E.
- Cherenkov radiation: EM shockwave, when speed of particle > local speed of light
- Transition radiation: emitted when particle moves from one medium to another

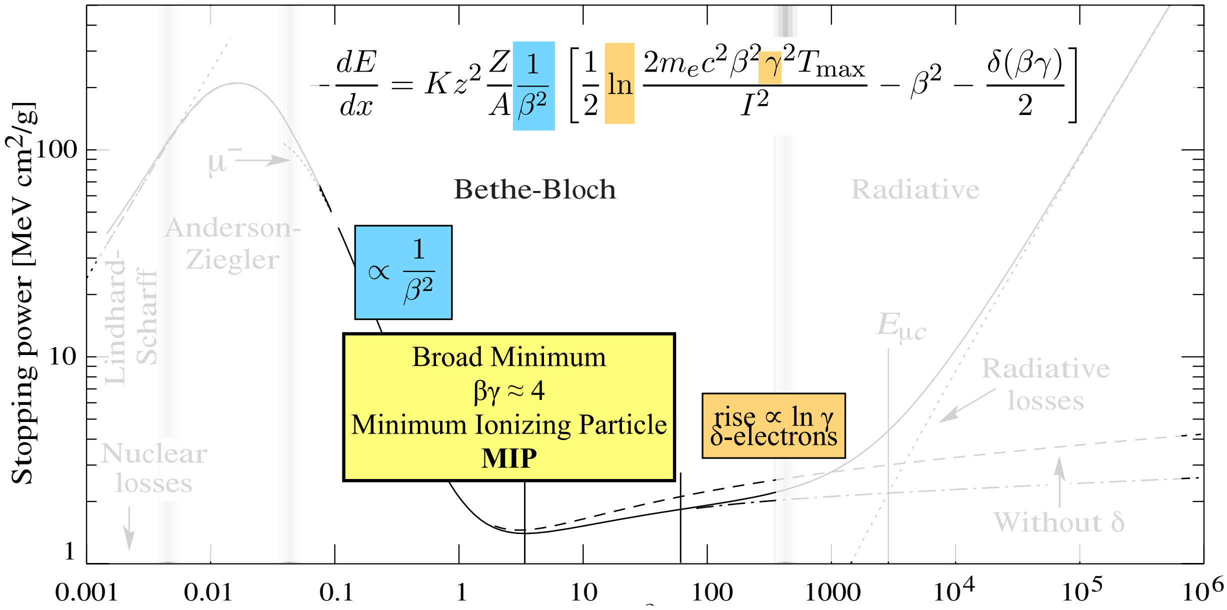
- Measuring the ionisation space points, dE/dx, and E, allows us to measure the momentum and energy of charged particles.

Energy Loss from Ionisation (Stopping Power)

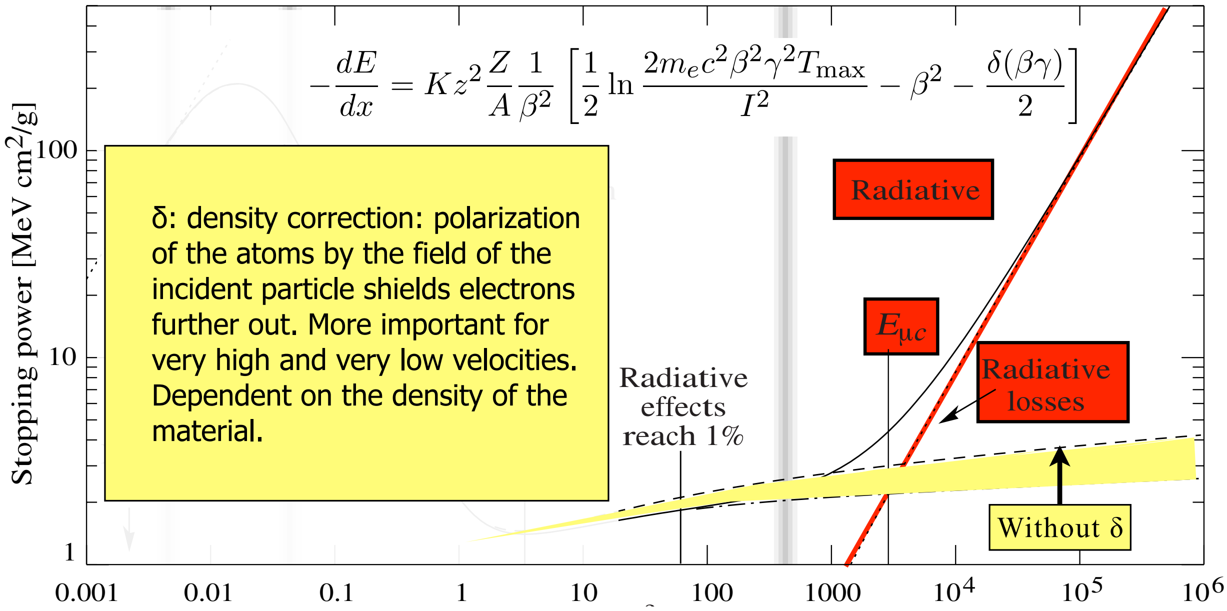


- ➡ ***dE/dx*** **- particle energy lost per *x* [MeVg^{-1}cm^2]**
- ➡ ***x*** - distance travelled by particle
- ➡ ***Z, A*** - atomic and mass number of medium
- ➡ ***I*** - excitation energy of medium
- ➡ ***ρ*** - density of medium
- ➡ ***T_{max}*** - maximum allowed kinetic energy transferred

Energy Loss from Ionisation (Stopping Power)

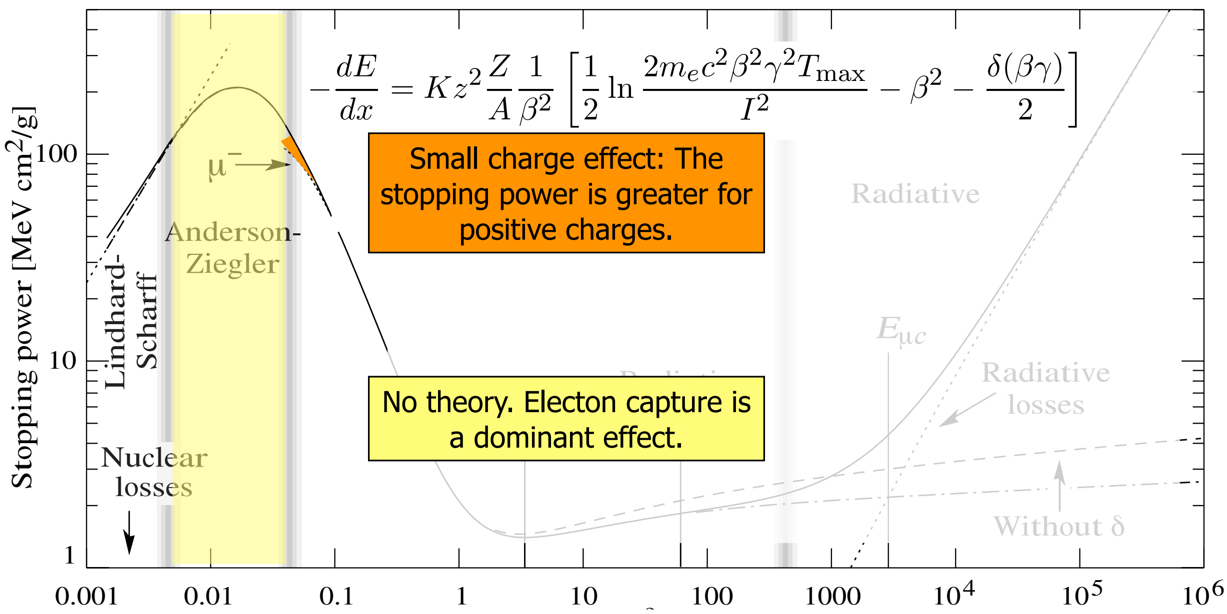


Energy Loss from Ionisation (Stopping Power)



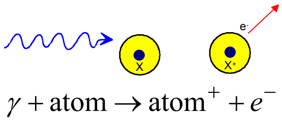
Above a critical energy energy losses by Bremsstrahlung become dominant.

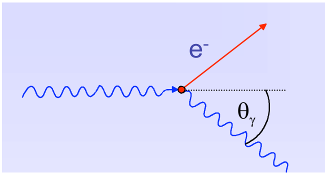
Energy Loss from Ionisation (Stopping Power)

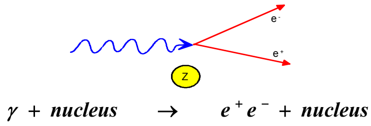


Interactions of Photons and EM Showers

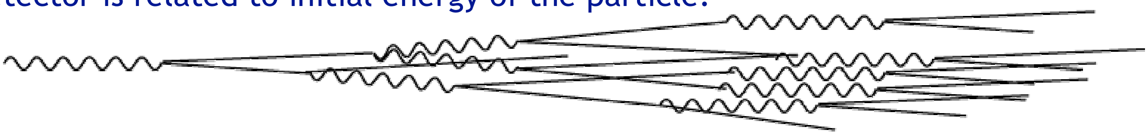
- Photons create charged particles (*e.g.* $\gamma \to e^+e^-$) or transfer energy to charged particles:
  - low energies (<**100 keV**): Photoelectric effect
  - medium energies (~**1 MeV**): Compton scattering
  - high energies (> **10 MeV**): $e+e-$ pair production in electric field of nucleus







- Electrons lose energy by Bremsstrahlung: $e^- \to e^-\gamma$
- Positrons annihilate with electrons in matter making pairs of photons: $e^+e^- \to \gamma\gamma$
- For $e+$, $e-$, γ: end result is an **electromagnetic shower**. Total energy transferred to detector is related to initial energy of the particle.



ATLAS Tracking

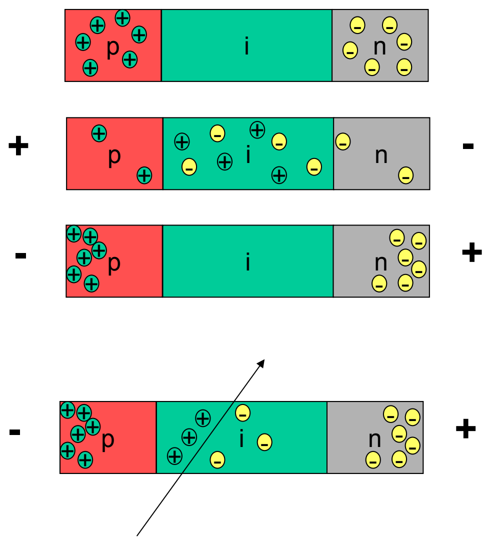
- Charged particle trajectories are curved in magnetic fields.
- Use the curvature, ρ, to measure the momentum transverse to the field, p_T.

$$p_T[\text{GeV}/c] = 0.3\, B[\text{T}]\, \rho[\text{m}]$$

- **Old method**: use a homogenous substance to trace out the entire motion.
- **Modern method**: take several position measurements as charged particle passes. Reconstruct a '**track**'

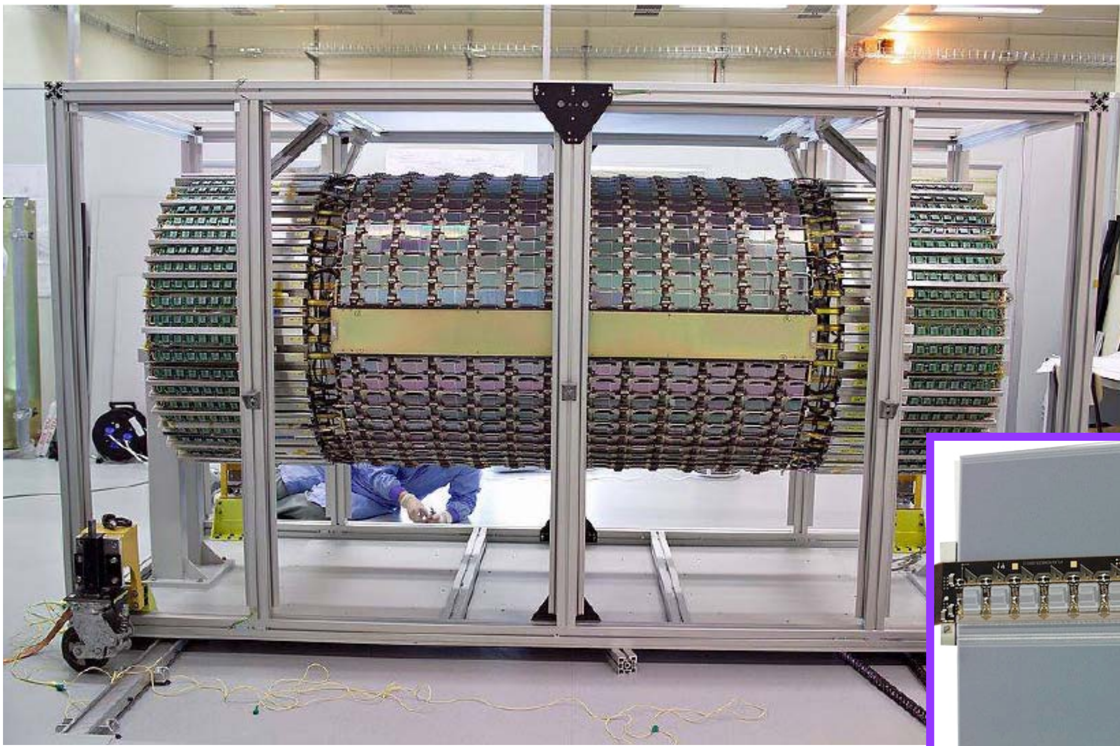
- ATLAS has three tracking detectors at increasing radii:
  - Pixel subdetector: made of silicon semiconductor. Pixelated to measure x,y and z position of hits.
  - SCT subdetector: silicon strips modules. Measure x and y position; z is defined by which module is hit.
  - TRT subdetector: measures x and y and time of hits. Also exploits transition radiation emitted by charged particles as they cross between plastic fibres and air in TRT. Use this signal to help differentiate between $e^\pm$ and $\pi^\pm$.

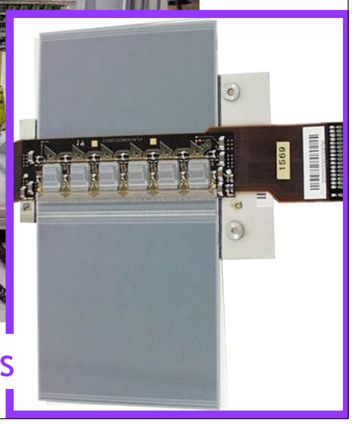
Semiconductor: Detection Principle



- Diode with **p-material** (positive holes) and **n-material** (negative electrons).
- Forward bias: a current flows, electrons and holes recombine
- Reverse bias: no current flows.
- Reverse bias: a short current pulse is created by a charge particle.

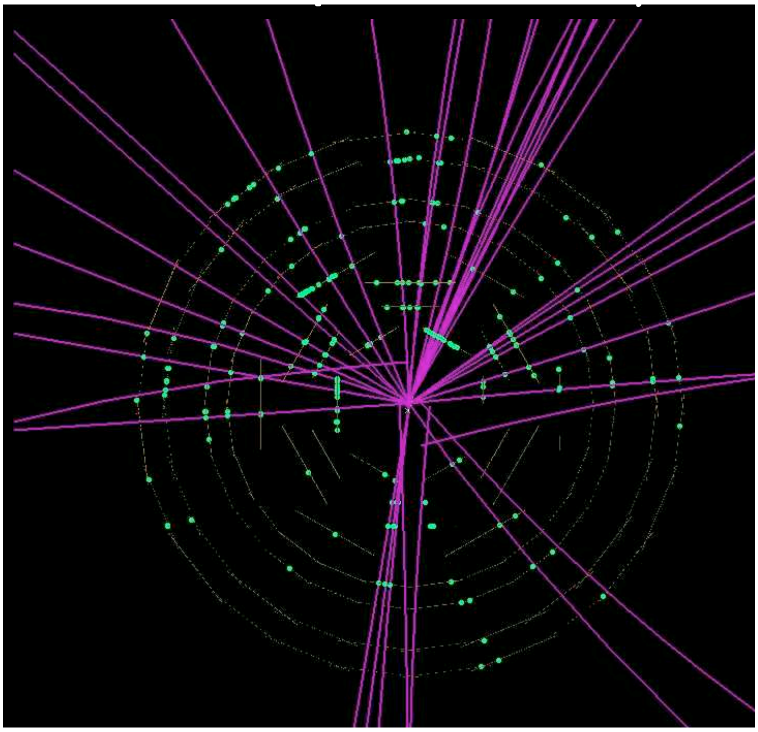
ATLAS SCT Tracker





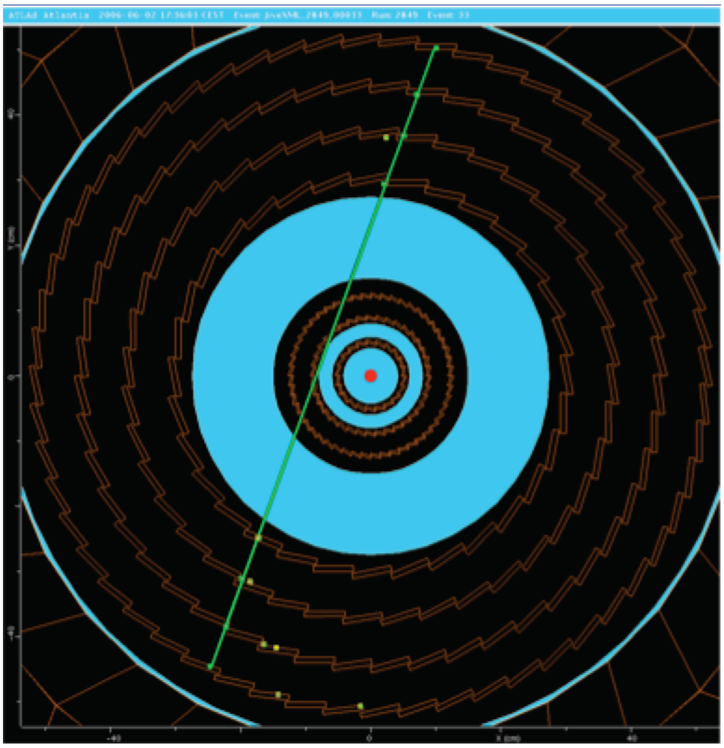
4084 modules

Reconstructing decay vertices



- Precise tracking allows particle decay vertices to be reconstructed.
- Did the particles originate from the *pp* scattering, or from decays of secondary particles?
- Essential for identifying signals from bottom and charm quarks - key for Higgs discovery!

ATLAS SCT Cosmic Muon Track

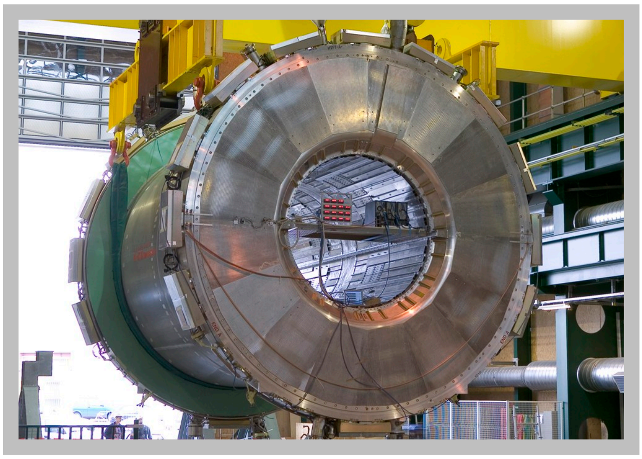


Signal from a muon produced in the upper atmosphere

ATLAS Calorimetry

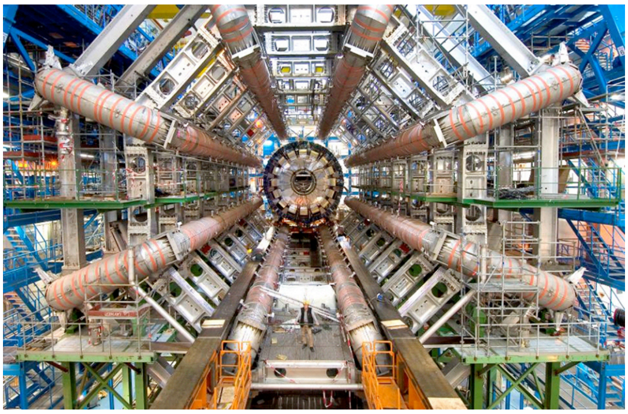
- **Calorimeters** measure the energy deposited when particles are absorbed.
- Electrons, positrons and photons are mainly absorbed in the **electromagnetic calorimeter**.
- Hadrons: ($\pi^{\pm}$, $K^{\pm}$, K^{0}, p, n) are mainly absorbed in the **hadronic calorimeter.**
- ATLAS uses a **sampling calorimeter**: samples parts of the electromagnetic or hadronic shower. Extrapolate to determine the full energy.
- Better energy measurements may be made using a **homogeneous calorimeter** - which measures *all* deposited energy

  - ATLAS calorimetery is based on liquid argon - 50000-litres all kept at −185C.
  - Electromagnetic calorimeter is made of liquid argon and lead electrodes.
  - Hadronic calorimeter is copper plates plus liquid argon.



ATLAS Magnets

- The higher the magnetic field, the more precise the momentum measurement.
- ATLAS has both a solenoid field and torroid magnets to enable the magnetic field return.
- The solenoid is a superconducting magnet kept at 4.5 K

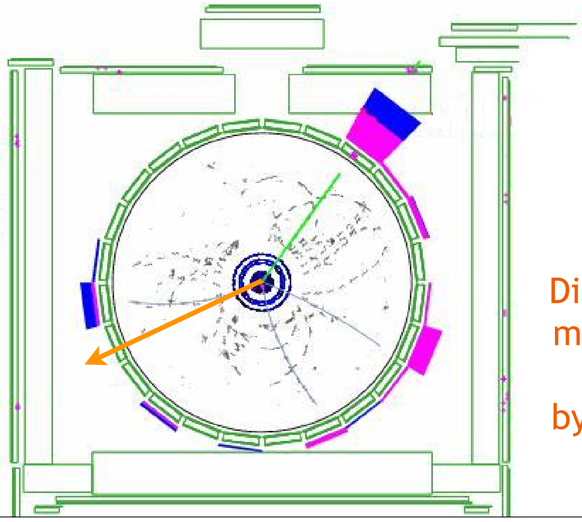


Neutrino Identification at ATLAS

- Neutrinos are not charged and only interact via the weak force
  ⇒ they do not interact at all in the detector.

$$\sum \vec{p}_{\text{initial}} = \sum \vec{p}_{\text{final}}$$

  - The initial momentum of the collision is along beam direction, no perpendicular component.
  - Total reconstructed momentum perpendicular to the beam should sum to zero.
  - We infer neutrinos from absence of momentum seen in a particular direction.



Direction of momentum carried by neutrino

Summary

- **Particle detectors** strive to reconstruct all long-lived particles.
- System of complex subdetector systems used to reconstruct position, momentum, energy, charge and particle type.
- The ATLAS detector consists of: an inner tracking detector, in a magnetic field, surrounded by an electromagnetic calorimeter, a hadronic calorimeter and a muon detector.
- Tracking: a non-destructive measurement of charged particle momentum. Charged particles loose energy due to ionisation. Ionisation signals are used to trace out a curved 'track', used to reconstruct the momentum.
- Calorimeters: destructive measurement. Particles exchange energy with calorimeter, through EM or strong interactions. Eventually most energy is absorbed and hence measured.
- Muon subdetector: muon don't interact very much (minimal ionisation loss). Muon subdetector detects everything which isn't absorbed in calorimeter which is mainly muons.
- Neutrinos don't interact at all. Infer their presence from lack of momentum balance.