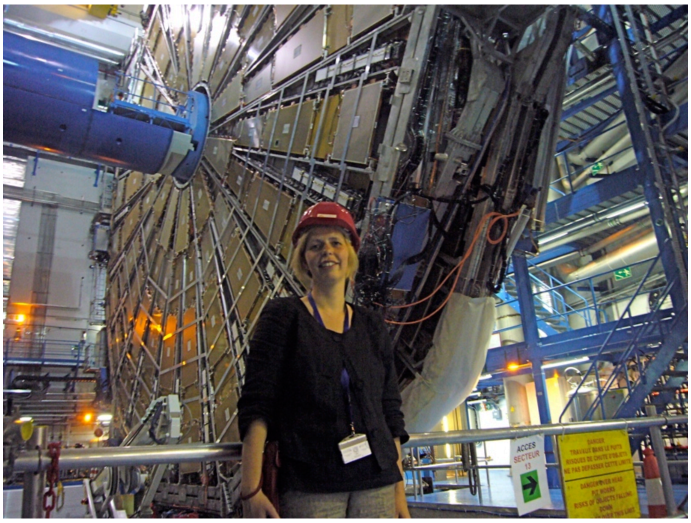
Subatomic Physics:

# Particle Physics Handout 6

## Particle Detection (with the ATLAS Detector)

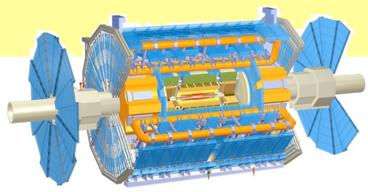


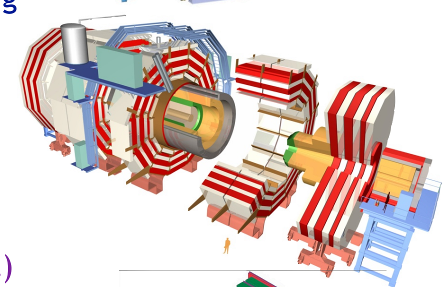
- **Particle Detectors:**
  - The ATLAS detector
  - Interactions of particles with matter
  - Particle reconstruction

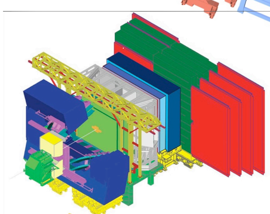
Learn the **concepts** about **which particles can be detected and how**: not the **details** about how the these concepts are implemented in ATLAS.

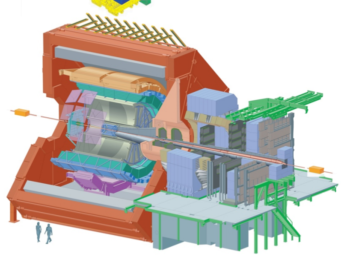


# Introduction





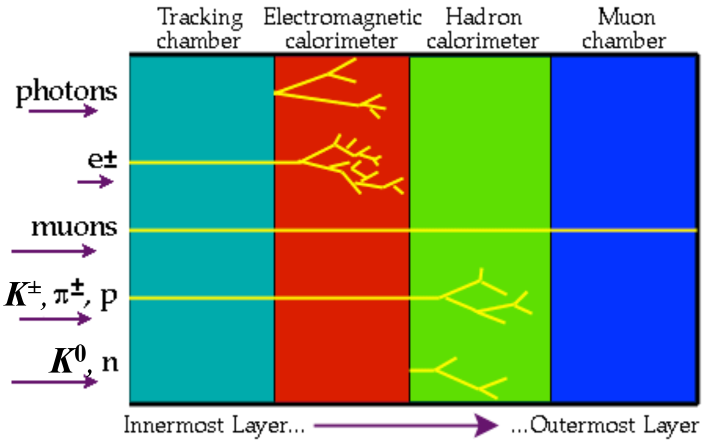




- Each of the four LHC collision point is surrounded by one of LHC experiments: ATLAS, CMS, LHCb, ALICE.
- The detector aims to detect all particles that live long enough to interact with the detector.
- For each final state particles try to measure:
  - Energy and momentum
  - Trajectory through the detector
  - Electric charge
  - Identity of particle (*e.g.* 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 reconstruct these particles.
- Infer the existence of shorter-lived particles from the decay produces.

# Interactions with Matter

- Generally a detector consists of a tracking chamber, an electromagnetic and hadron(ic) calorimeter and a muon chamber in a magnetic field.
- Each experiment uses different technologies to construct the subdetectors.



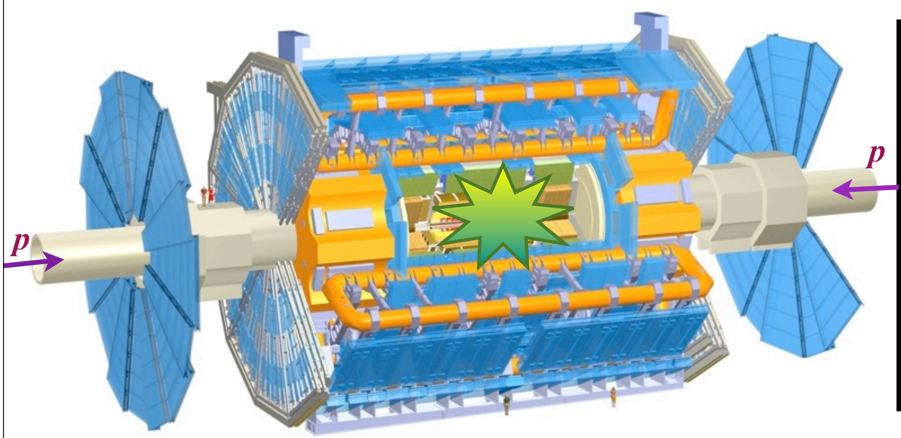

- Tracking measures charged particle trajectory and momentum without destroying the particle.
- Calorimeter layers measure energy by fully absorbing the particles (destructive measurement).
- Muons do not interact in calorimeter very much: final detection layer to detect muons.

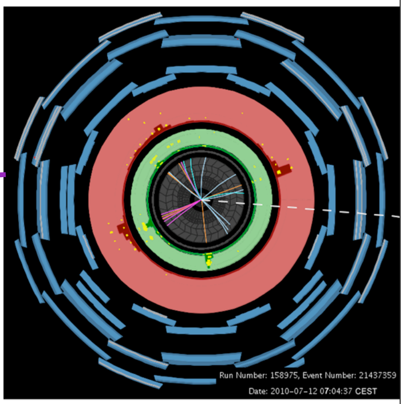


# The ATLAS Detector

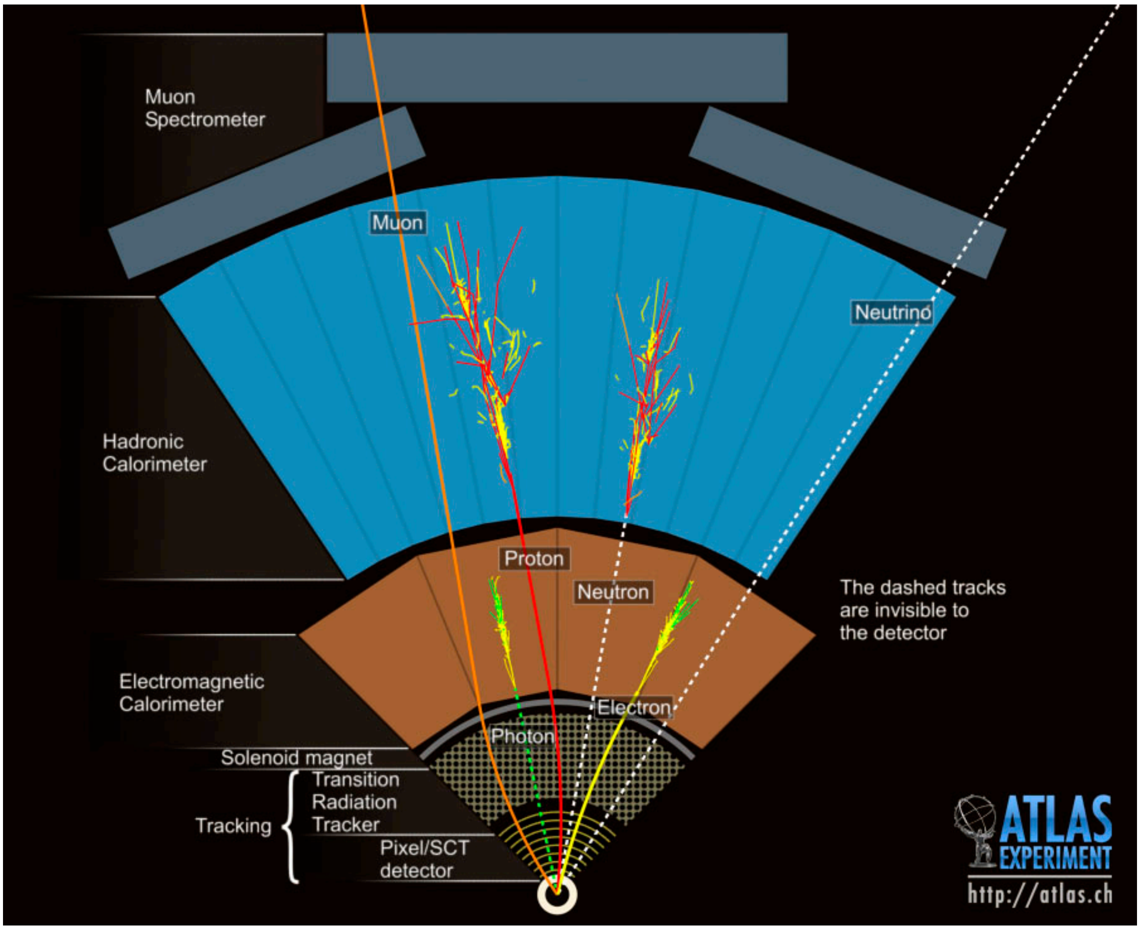
- Most general purpose collider detectors are conceptually similar
- ATLAS is a cylinder with a total length of 42 m and a radius of 11 m.

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



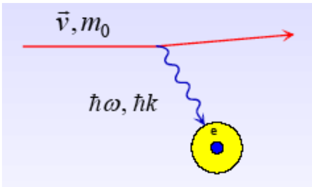

lots more at http://atlas.ch/






# 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**

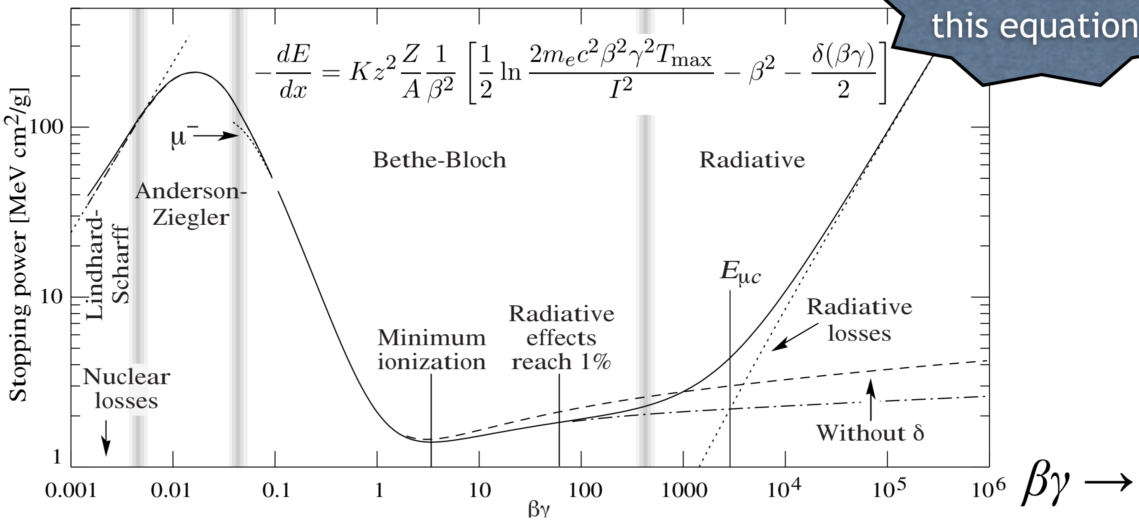



- A small amount of energy loss causes **ionisation**, e.g.:
  - ionisation of atoms in a gas
  - electron-hole creation in a solid state detector
- Use ionisation signal to identify space points where a charged particle has passed.
- Ionisation energy loss per distance travelled, ***dE/dx***, is given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

# Model of Energy Loss due to Ionisation

- Model is based on radiative and nuclear interactions between particles travelling through the detector and the detector.
- Use model to estimate $E_{lost} = \int dE/dx\, dx$ by particle travelling through the detector, as a function of particle type and particle energy.
- Measure $E_{lost}$ in detector - used to identify particle type.

Do not learn this equation!

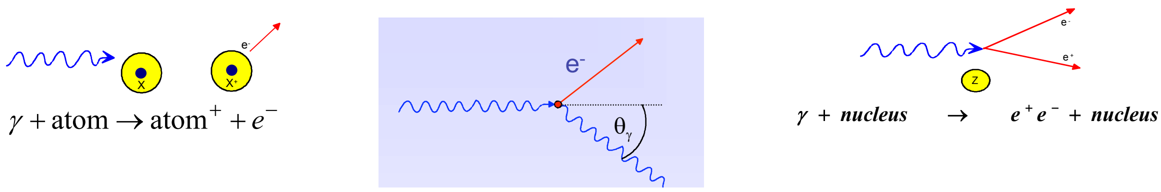



- $dE/dx$ - particle energy lost per distance $x$ [$\mathrm{MeVg^{-1}cm^2}$]
- $x$ - distance travelled by particle
- $Z, A$ - atomic and mass number of medium
- $I$ - excitation energy of medium
- $\rho$ - density of medium

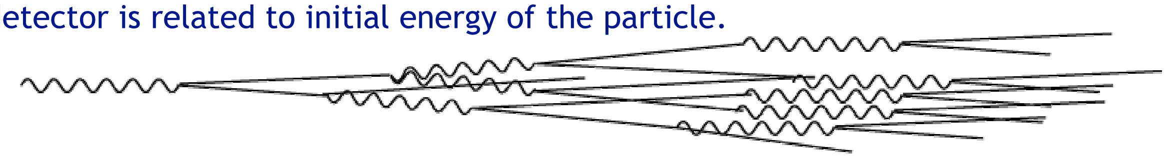


# Interactions of Photons and EM Showers

- 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 $e+$, $e-$, $\gamma$: end result is an electromagnetic shower. Total energy transferred to detector is related to initial energy of the particle.



# Tracking: Reconstructing Charged Particles

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

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

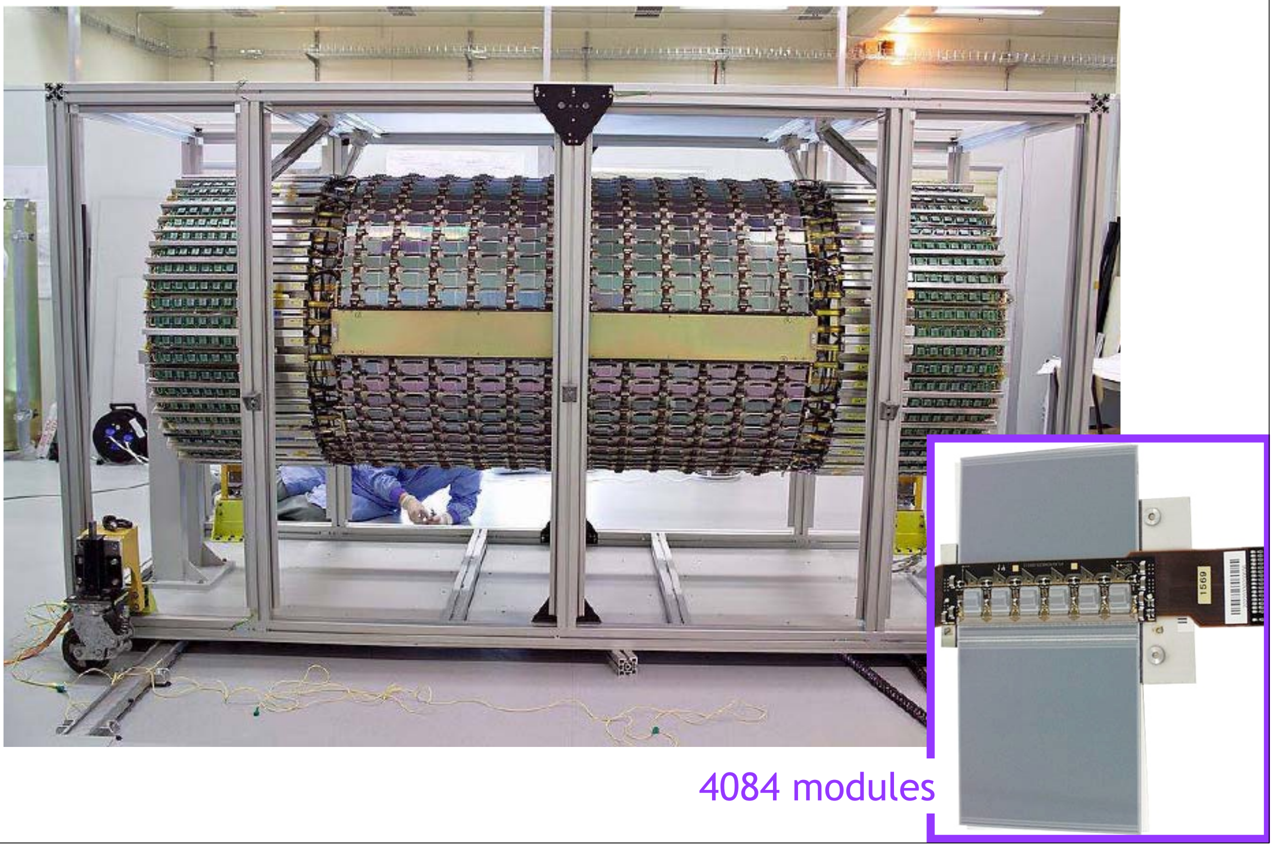
- **Old method**: use a homogenous substance to trace out the entire motion.
- **Modern method:** take several position measurements (sometimes also time measurements) as charged particle passes.
  - ➡ These position measurements are used to reconstruct a '**track**': the trajectory of the charged particles through the detector.

- 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 $\pi^{\pm}$.



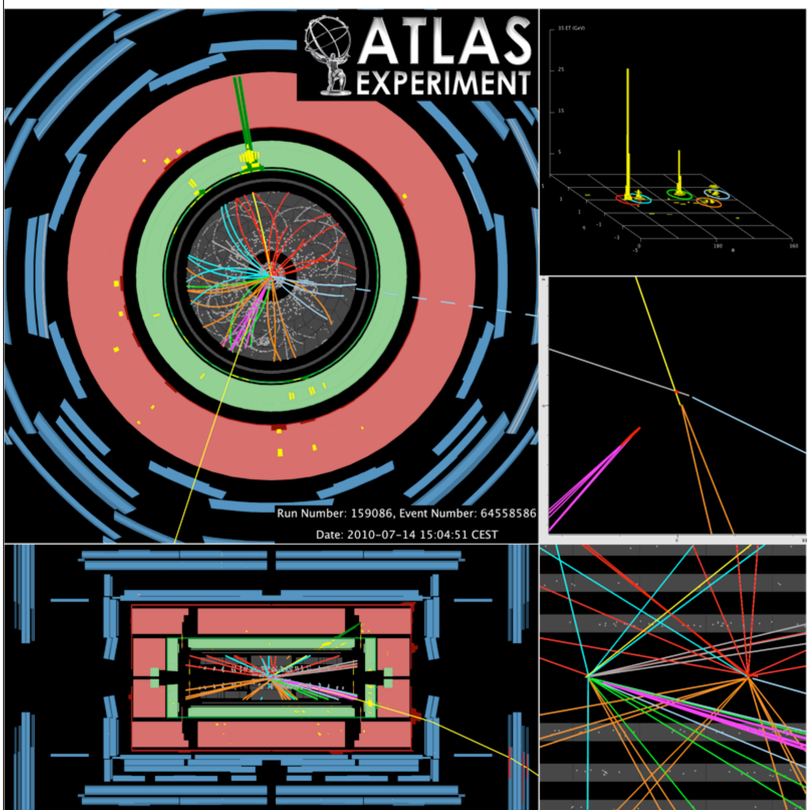
# Inserting the Pixel Detector into ATLAS

# ATLAS SCT Tracker






# Reconstructing Decay Vertices

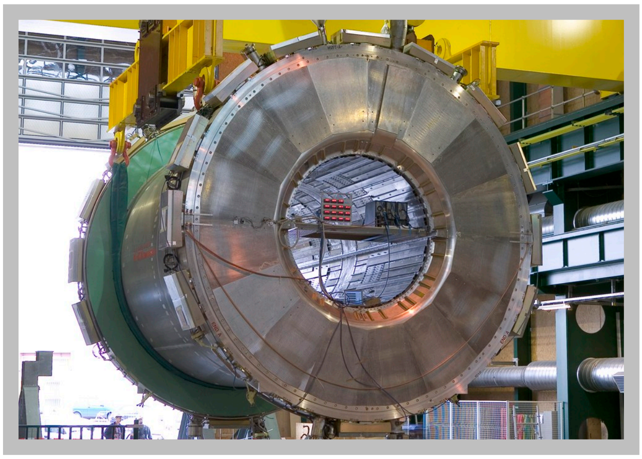



- Precise tracking allows particle **decay vertices** - the position where a short-lived particle decayed - to be reconstructed.
- Did the particles in the detector originate directly from the $p\,p$ scattering, or are they from decays of secondary particles?
- e.g. This is essential for identifying signals from bottom and charm quarks - key for Higgs discovery!

# 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

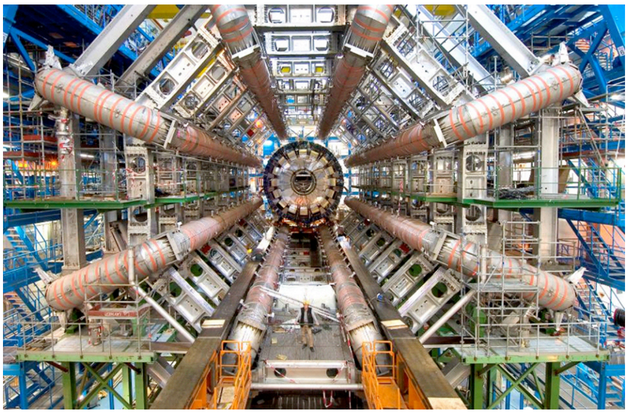
  - ATLAS calorimetery is based on liquid argon - 50000-litres all kept at −185C.
  - Electromagnetic calorimeter is made of liquid argon and lead electrodes.
  - Hadronic calorimeter is copper plates plus liquid argon.





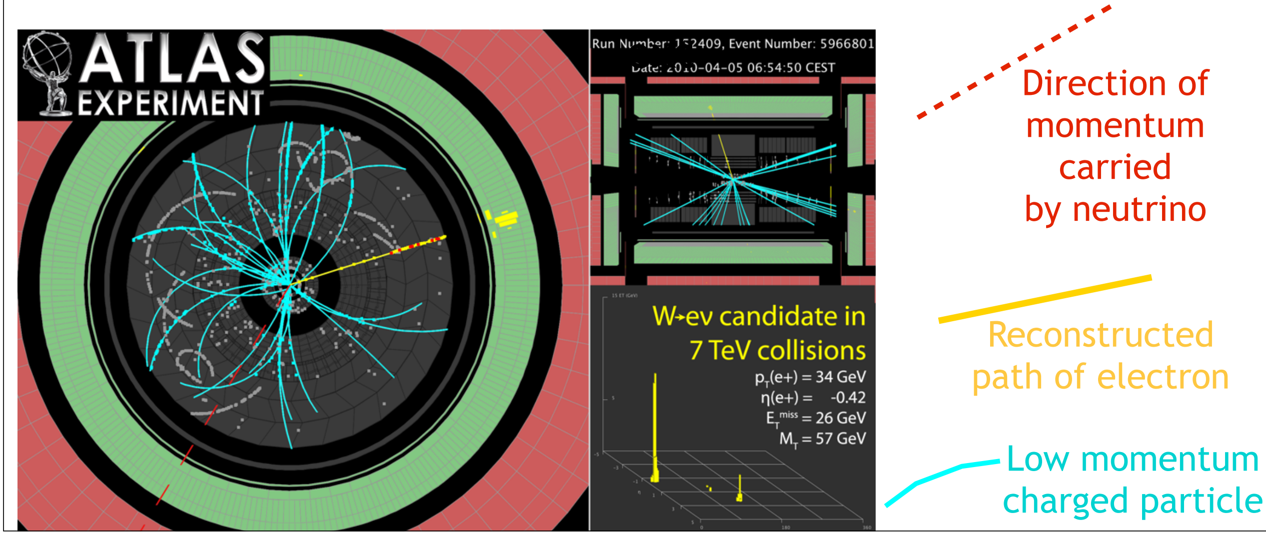
# Magnets

- 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 Colliders

- Neutrinos are not charged and only interact via the weak force
  ⇒ they do not interact at all in the detector. $\sum \vec{p}_{\mathrm{initial}} = \sum \vec{p}_{\mathrm{final}}$
  - The initial momentum of the collision is along beam direction: no initial momentum perpendicular to beam direction.
  - Total momentum of the perpendicular to the beam should sum to zero.
  - We infer neutrinos from absence of momentum seen in a particular direction.






# 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: a tracking detector, surrounded by an electromagnetic calorimeter, a hadronic calorimeter and a muon detector in a magnetic field.
- 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.