HEP-101 Lecture

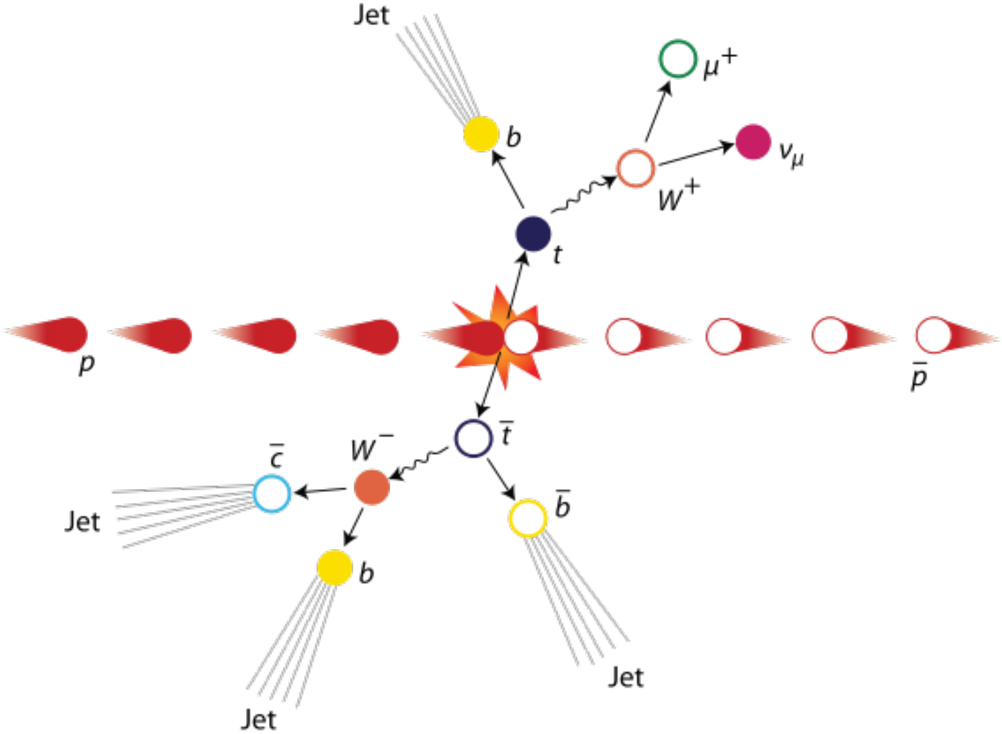
Principles of Particle Detection

Mark Kruse, 20 March 2017

Introduction

- What we need to detect, and distinguish, are the "stable" particles resulting from the high-energy collisions (in the case of the LHC proton-proton collisions at 7-14 TeV)

- We then use these detected particles to try and reconstruct the physics process that produced them



What we detect are “stable” particles

- Photons; γ
- Electrons; $e^{\pm}$
- Muons; $\mu^{\pm}$
- Neutrinos; ν
  (indirectly – more later)

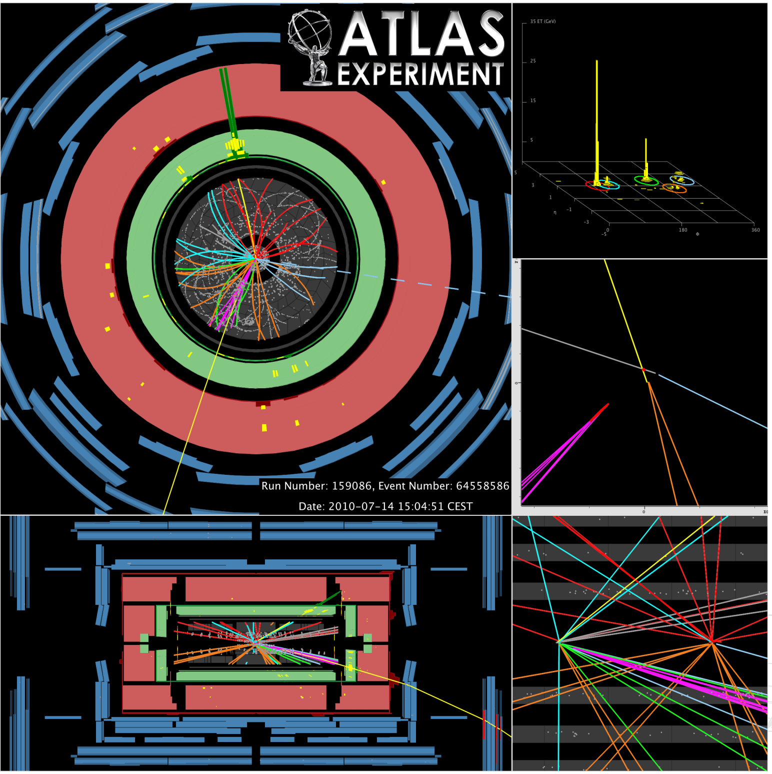
- Pions; $\pi^{\pm}$, π^{0}
- Protons; p, $\bar{p}$
- Neutrons; n
- Kaons; $K^{\pm}$, K_L^{0}
- ….

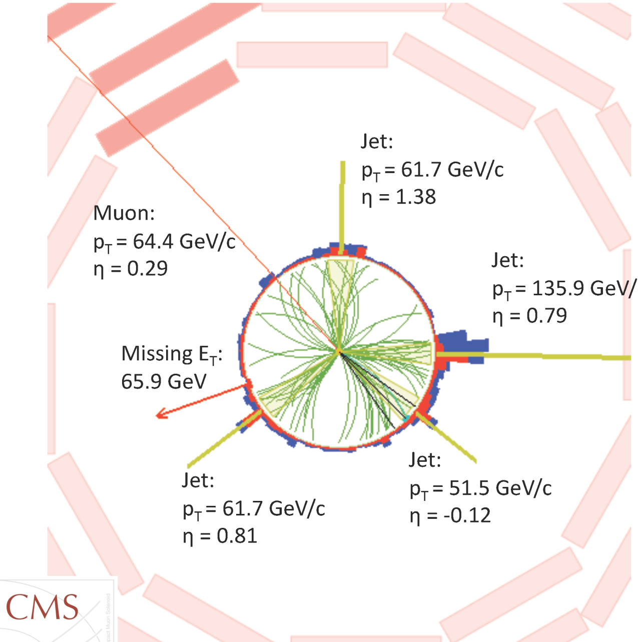
But, for example, $\tau_\mu \approx 1 \times 10^{-6}$s – how is that stable ?

- Exercise in the relativistic kinematics you have learned
- Typical muon energy, $E_\mu = 20$ GeV
- Muon rest mass, $M_\mu = 106$ MeV/c^2
- $E_\mu = \gamma M_\mu c^2 \Rightarrow \gamma \approx 200$, $v \approx c$
- Typical distance travelled before decay, $d \approx \gamma\tau_\mu c =$ 60km !

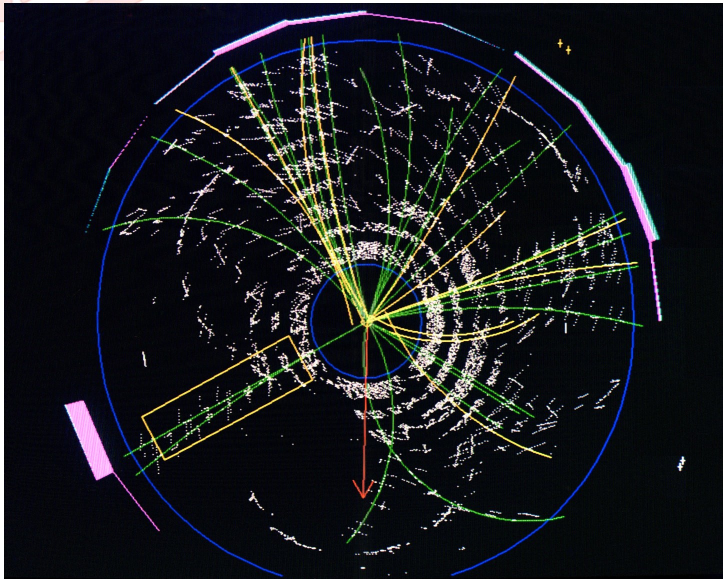
- So muons can easily travel through the ATLAS detector before decaying

Comparison of HEP detectors





CDF



- Notice the broad similarity !

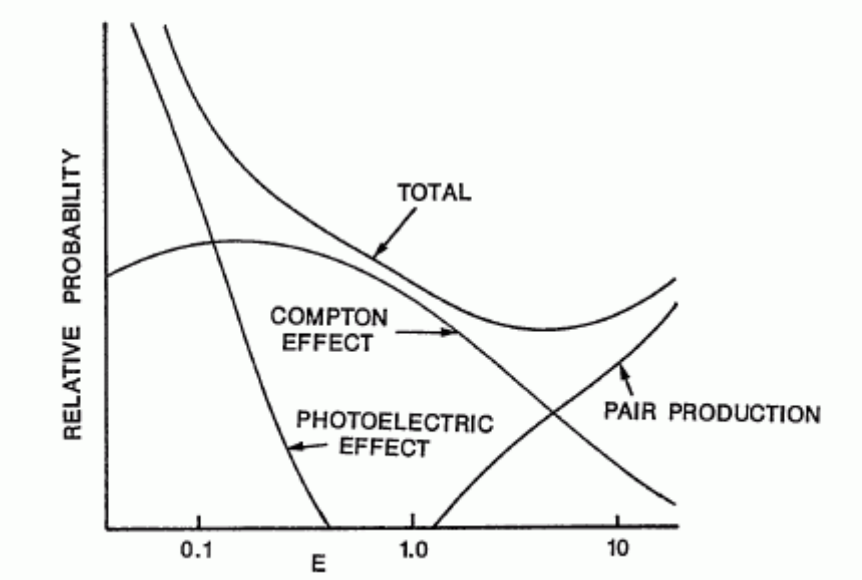
Basic principles of **charged** particle detection

- Particles loose energy/deflect in the detector medium through:
  - Inelastic collisions with atomic electrons
    - Leads to ionization of the medium and therefore electrical currents which are read out
  - Bremsstrahlung
    - In the field of nucleus light particles (such as e+, e-) loose energy by emission of "Bremsstrahlung" photons (because particles are "accelerated")
  - Emission of Cherenkov photons
    - Not a large effect at the LHC
  - Elastic scattering from nuclei
  - Nuclear reactions

- In addition, detectors are immersed in strong magnetic fields to bend charged particles and hence measure their momentum

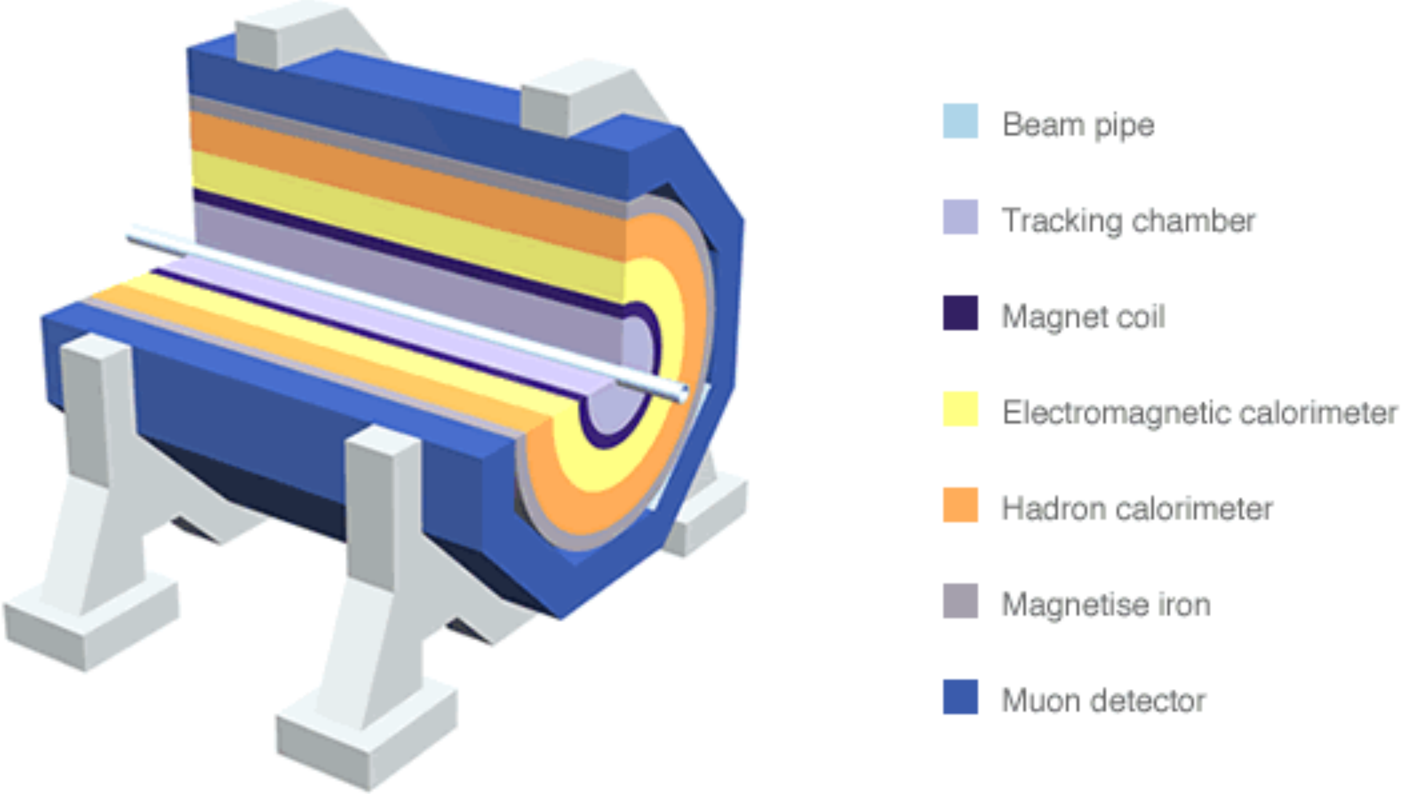
Basic principles of **neutral** particle detection

- For photons, energy loss through:
  - Photoelectric effect
  - Compton effect
  - **Pair production**



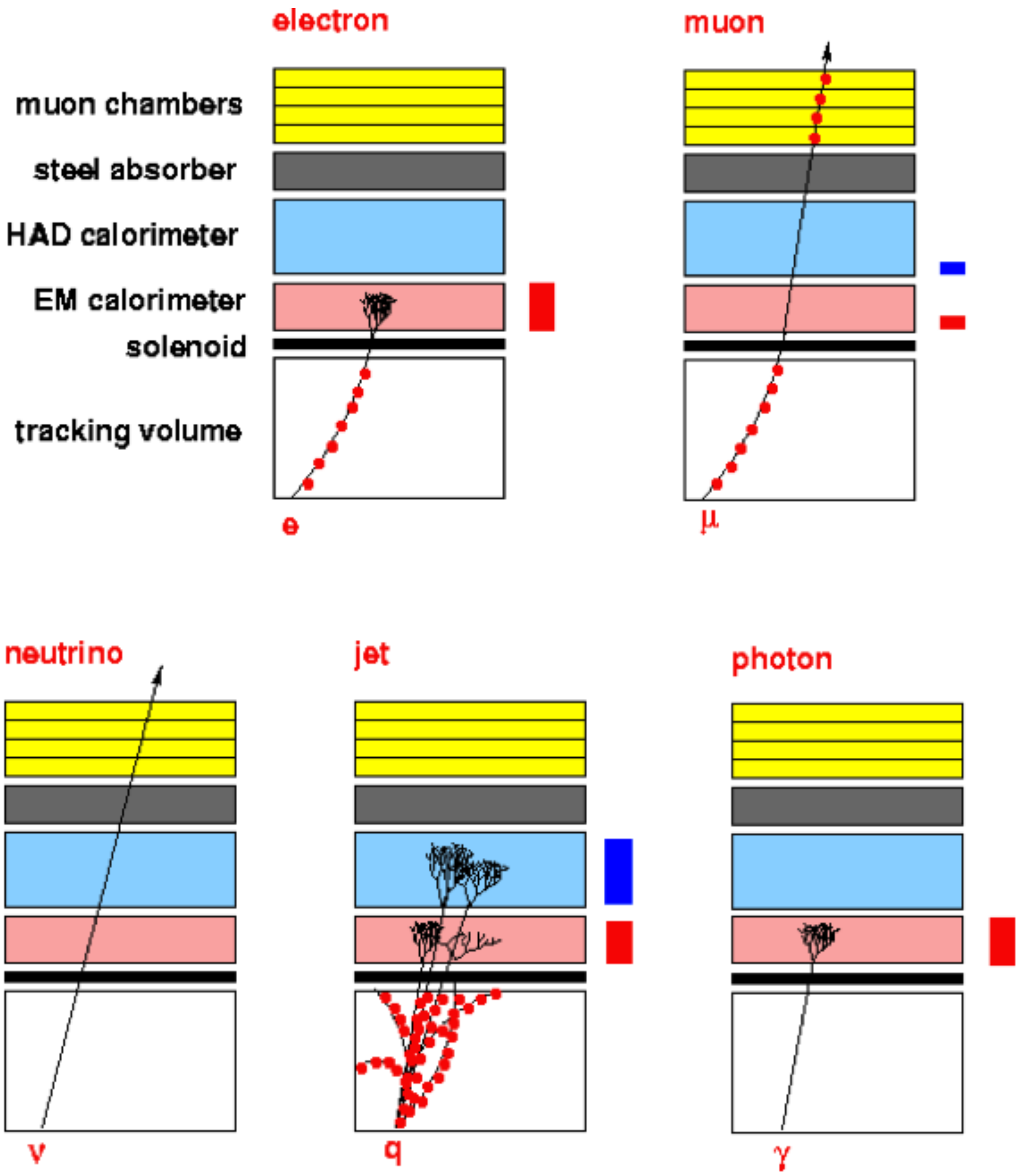
- Leads to "electromagnetic showers": photons pair produce, electrons radiate photons, …..
- Other neutral particles (e.g. neutrons, π^0, K_L^0) experience nuclear reactions with the nuclei of the detector medium, depositing their energy in the detector – parameterised by the "hadronic interaction path length", X_0
- Neutrinos only interact via the weak interaction and typically don't interact with the detector – their presence in an "event" can only be inferred indirectly (more on this later)

HEP detectors: general design



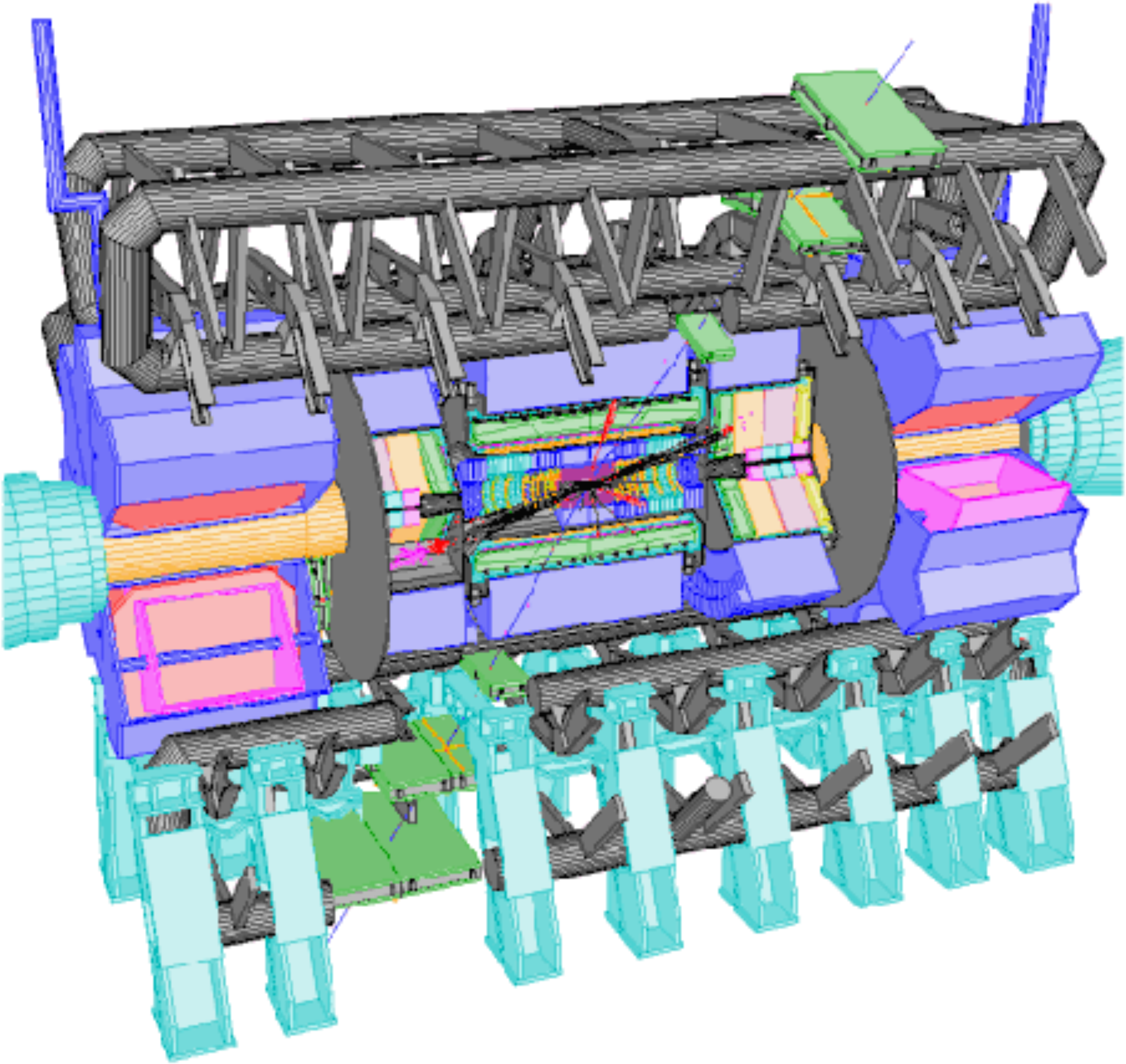
- All detectors in hadron collider experiments are broadly similar, based on being able to distinguish all stable final state particles:
  - Inner detectors for precision tracking, based on energy loss by ionization
  - Calorimeters for energy measurement (electromagnetic and hadronic)
  - Outer muon detectors for muon identification (again based on ionization)

Basic particle identification



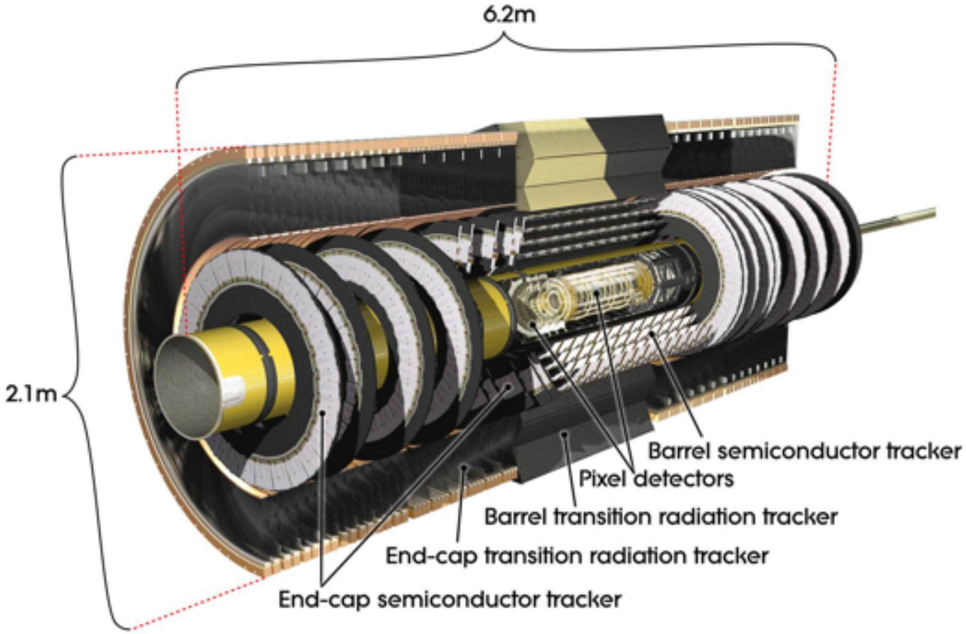
- Different particles lead to different and easily distinguishable signatures
- **Example:** both electrons and photons produce electromagnetic showers in the EM calorimeter, but only the electron produces an ionization track in the tracking detector

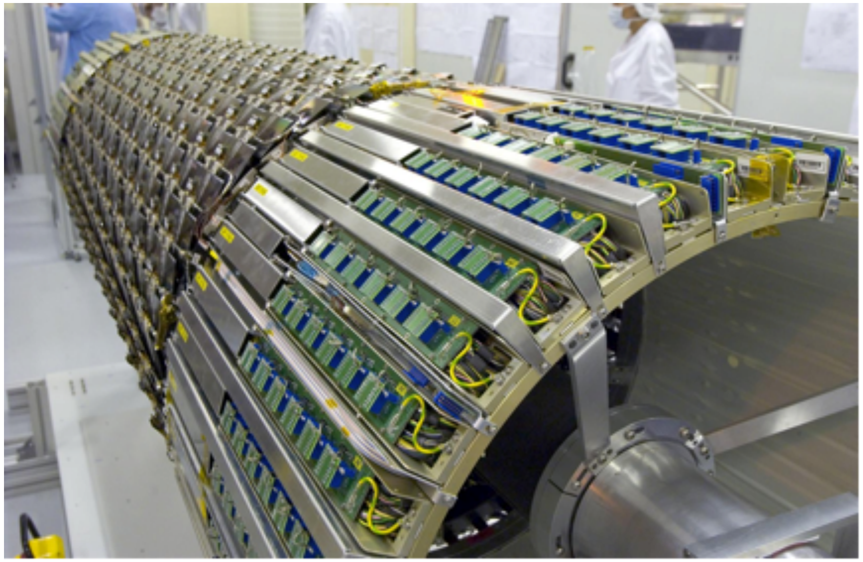
A closer look at ATLAS



The ATLAS Inner Detector (ID)

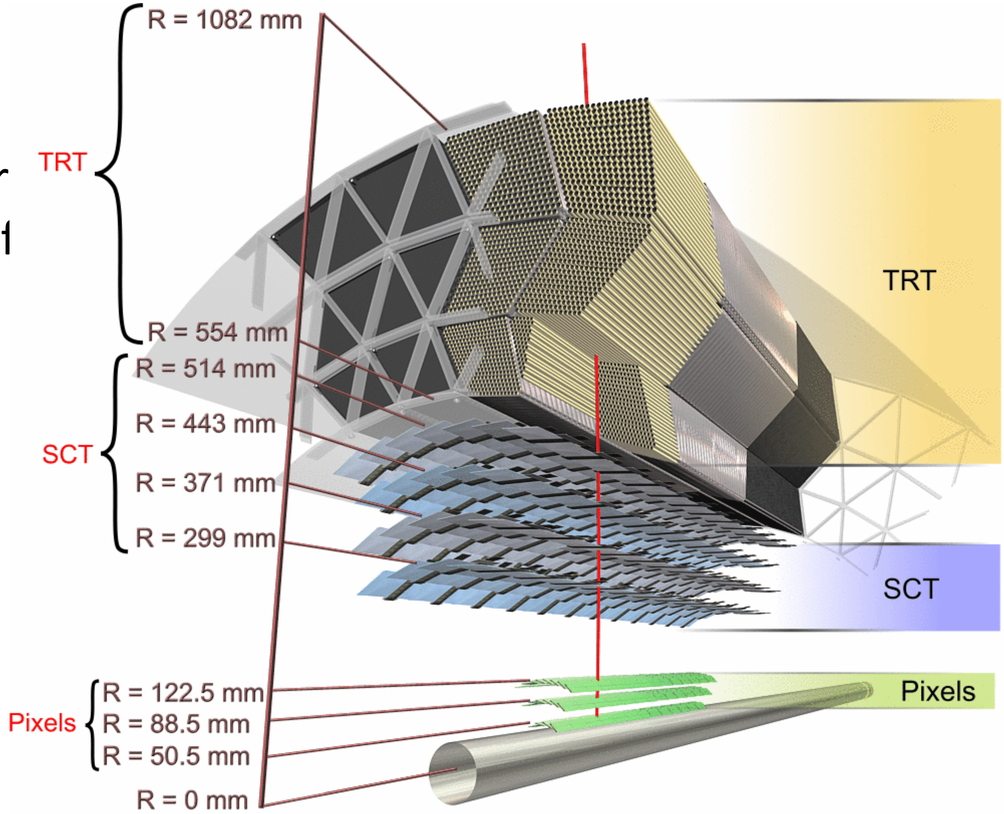
- **Basic principle**: particles are tracked via the ionization of the medium, losing very little energy
  - Ionizaton of silicon for the pixel and silicon strip detectors (more soon)
  - Ionization of gas for the Transition Radiation Tracker





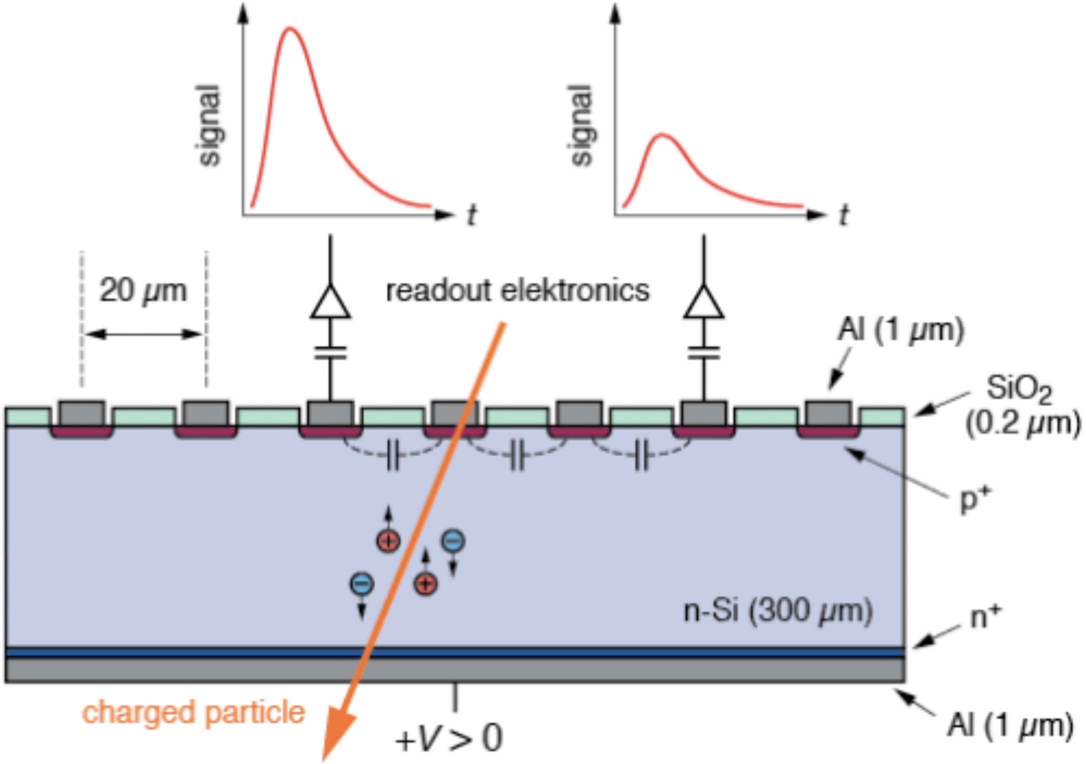
The ATLAS Inner Detector

- Three ID detector systems
  - Pixels and the SCT (silicon central tracker) based on silicon sensor technology – precision tracking for secondary vertex reconstruction of B hadrons
  - Transition Radiation Tracker (TRT) based on straw drift tubes for tracking and particle identification via transition radiation
  - Momentum resolution typically 2-3%
- Immersed in a 2 T magnetic field
- Tracking out to $|\eta| < 2.5$ ($\theta < 10^o$)



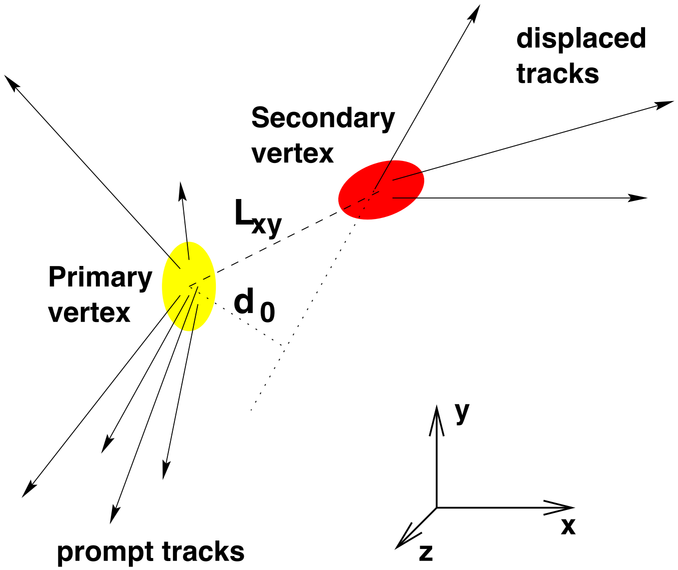
More on Silicon detectors

- Thin strips of silicon sensors have a voltage across them to produce a wide “depletion region” (across the existing p-n junction)
- Charged particles traversing the bulk silicon produce electron-hole pairs
- This charged is then read out and used to precisely locate the position of the particle
- The example being handed around is from the CDF silicon detector



Silicon detectors: usage as vertex detectors

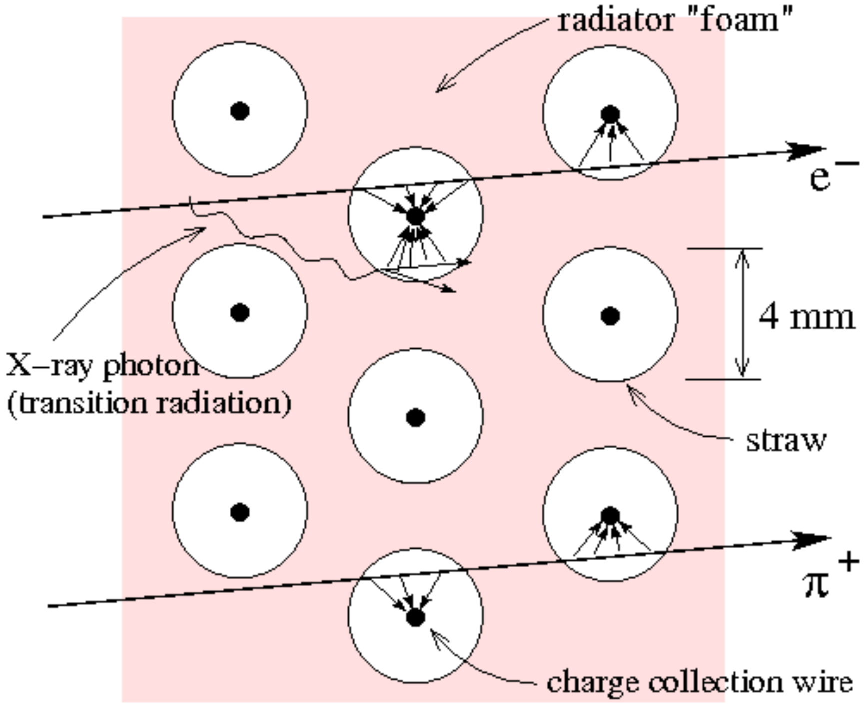
- An important use of silicon detectors is the precise determination of secondary vertices
- Hadrons formed with b quarks typically travel ~few mm before decaying
- It is important to distinguish "jets" originating from b quarks versus other lighter quarks
    - E.g. allows better signal to background for some important processes such as H ➔ bb, t ➔ Wb, etc….

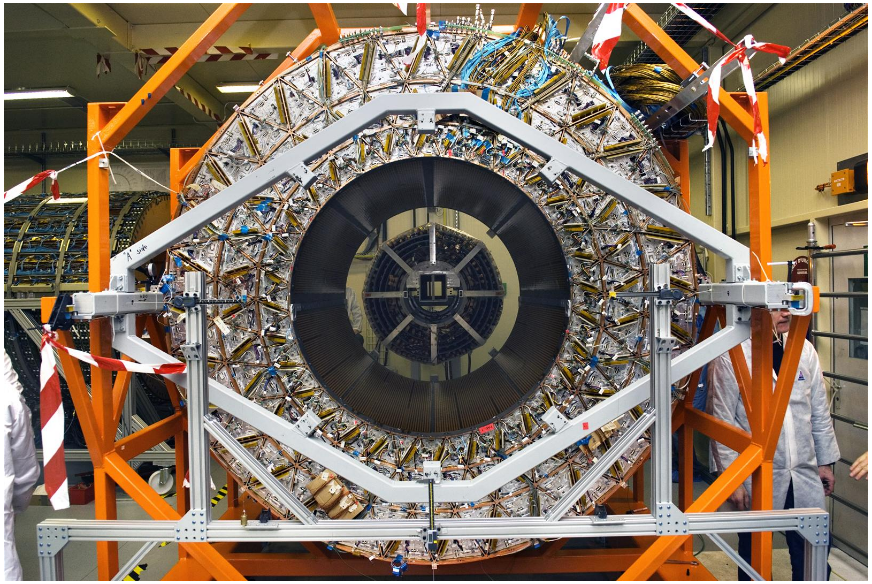


- Typically:
    - L_{xy} ~ 5 mm
    - ΔL_{xy} ~ 100μm
    - d_0 resolution ~ 20μm

TRT operation

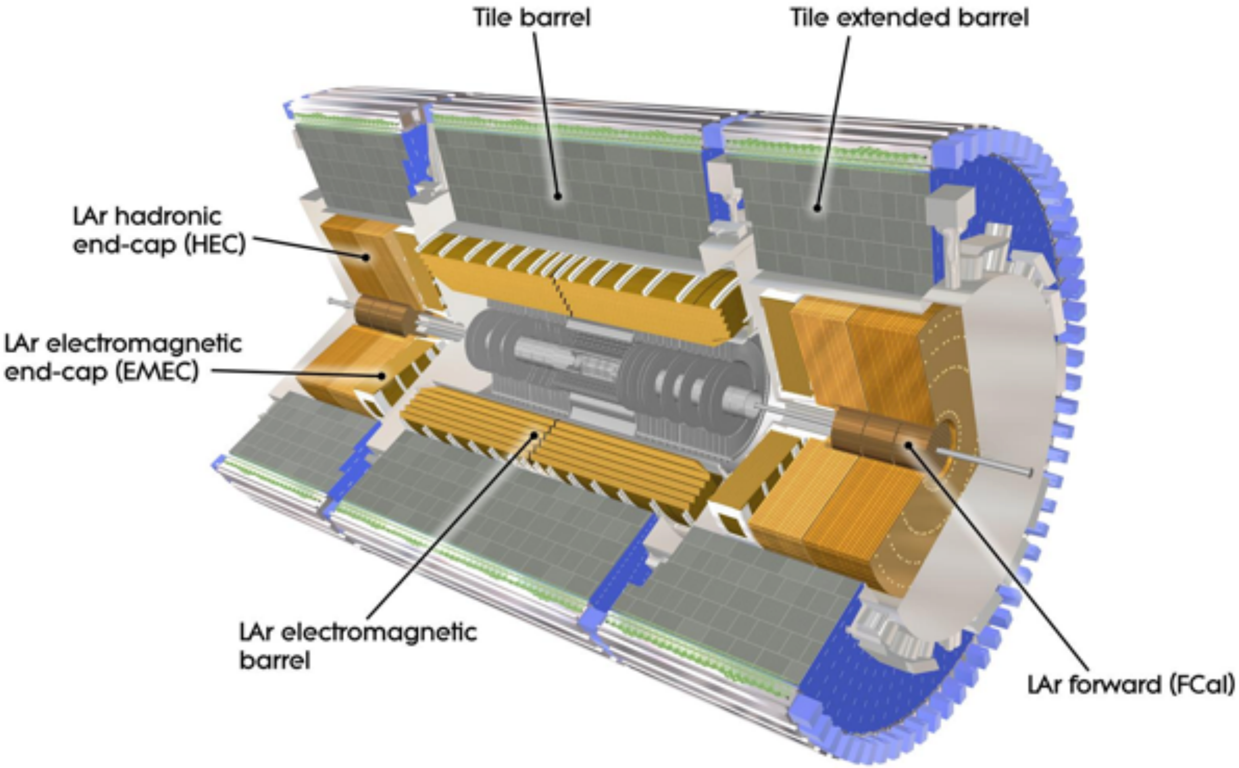
- ~60 straw layers, and about 370,000 straws, each 2mm in radius and filled with Xenon which is ionized by a traversing particle, allowing reconstruction of the particle trajectory
- Particles with $\gamma = (1 - \beta^2)^{-1/2} \sim 2000$ undergo "transition radiation" in the foam surrounding the straws allowing for particle identification (via $E = \gamma mc^2$)





ATLAS calorimeter detectors

- **Basic principle:** sheets of metal (absorbers) sandwiched between a detection medium. Particles interact with the absorbers, eventually losing all their energy, producing showers of secondary particles which are detected in the detection medium. The resulting signal is proportional to the incident particle energy.

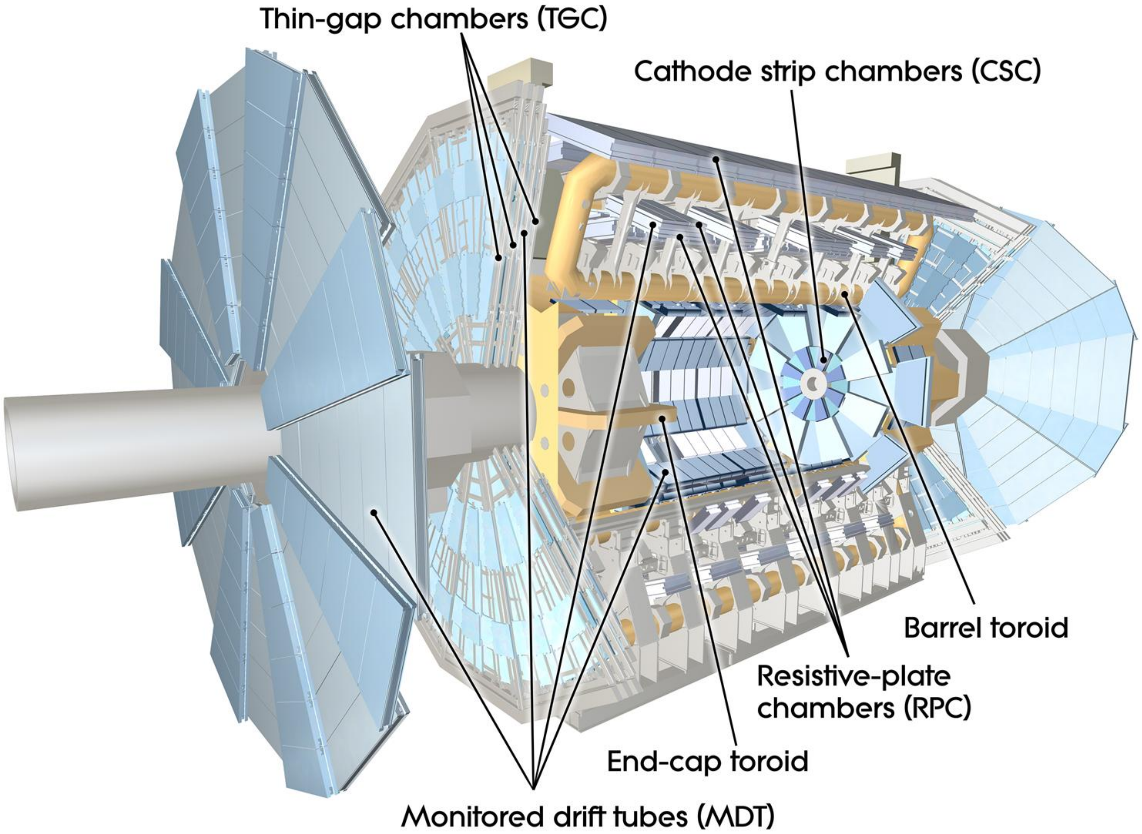


ATLAS calorimeter detectors: properties

- Electromagnetic Calorimeter:
  - Pb absorber / Liquid Ar ($|\eta| < 3.2$)
  - Absorbs all electrons and photons
  - E resolution: $10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\%$
- Hadronic Calorimeter:
  - Hadrons (eg. p, n, π) travel through EM CAL depositing some energy but typically stopping in HAD CAL.
  - Barrel: Iron / Tile ($|\eta| < 3.2$)
  - $\sigma_E/E \sim 50\%/\sqrt{E(\mathrm{GeV})} \oplus 3.0\%$
- EC/Fwd: Cu / LAr ($3.2 < |\eta| < 5$)
  - $\sigma_E/E \sim 100\%/\sqrt{E(\mathrm{GeV})} \oplus 10\%$

The ATLAS muon detectors

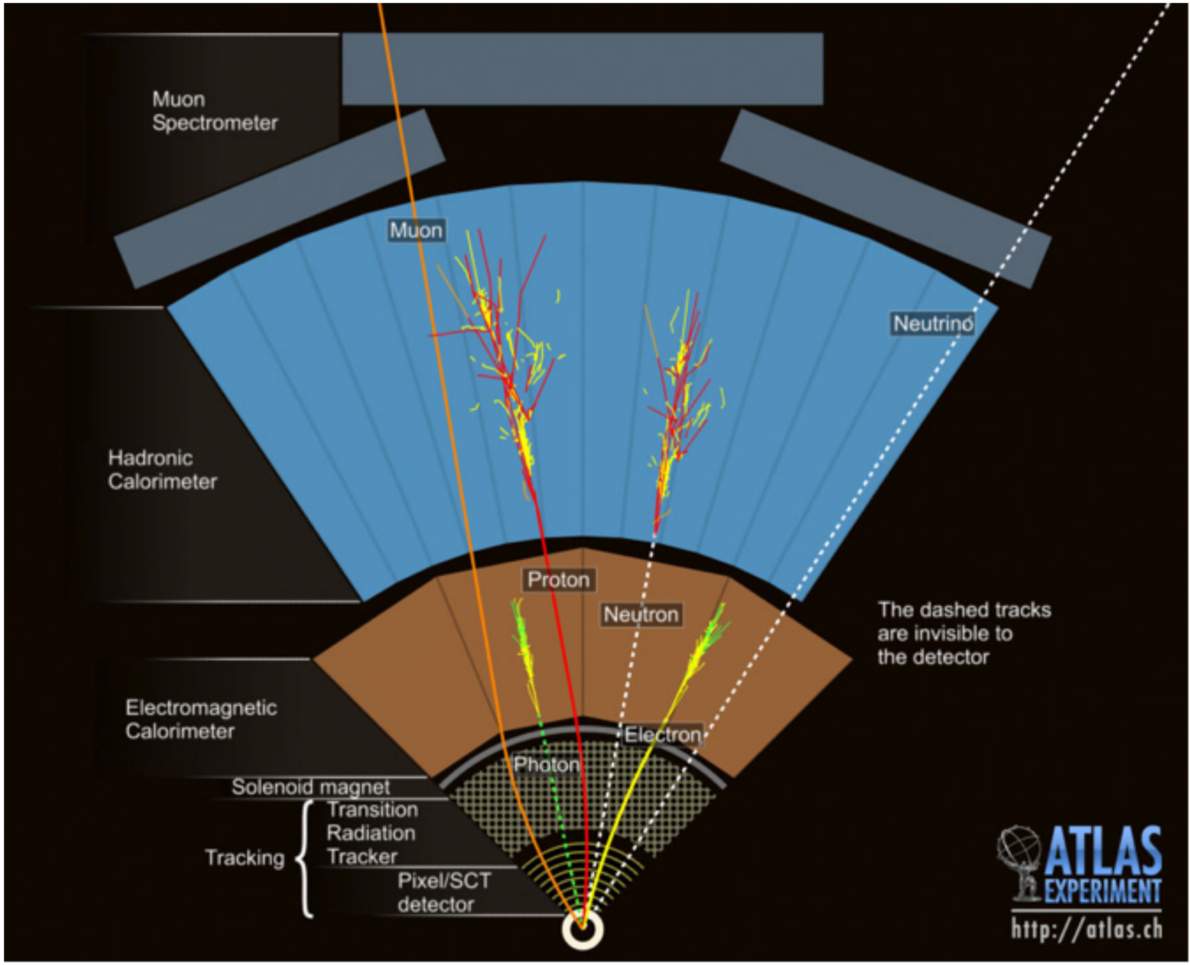
- **Basic principle:** the only particles that make it through the calorimeters are muons (and neutrinos!), so various ionization chambers exist outside the calorimeters to detect μ's: a ID track matched to a muon chamber track is a pretty good candidate for a muon.
- Standalone momentum resolution ~10%



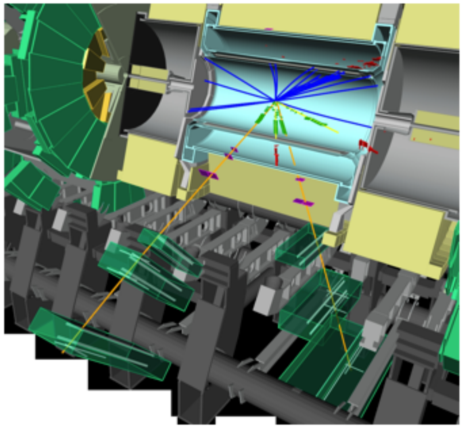
Putting all the detector pieces together

- What we detect are particles that are "stable", which, for a lot of interesting physics are the decay products of other particles:
  - e.g. H → WW → eν μν

- Then its a whole other lecture how we distinguish an event like this, produced every trillion collisions, that decays instantly into a cascade of other particles, and looks like several other processes that are produced orders of magnitude more frequently!



From detecting collisions to recording “events”



Bunch crossing rate
~ 40 MHz

3 Level Trigger Architecture to select “interesting” events

E.g. about 1 in 10^{11} collisions produces a Higgs event

Level 1: Uses Calorimeter, Muon system

~ 100 kHz

Level 2: uses reconstructed e/g, muons, jets

~ 4 kHz

Event builder/filter:
~1800 multicore PCs

~ 200 Hz

~300MB/s written to disk,
~3 Pbytes stored per year

Important parameters related to the detector

- A couple of important concepts related to the design of HEP detectors:
  - Transverse energy/momentum, E_T / P_T
  - Missing transverse energy, $\not{E}_T$
  - Pseudorapidity, $\eta = -\ln(\tan(\theta/2))$
    - E.g. $\theta = 45^o$ => $|\eta| = 0.9$

Summary

- Particle detectors in HEP work on the principle of energy loss, which can occur in several ways, for the particles that traverse the detector medium
- HEP detectors follow the same basic design: tracking, calorimetry, muon detection
- It is important to understand how the detector works to appreciate the algorithms used for particle identification
- This is only a broad introduction – you are encouraged to research more details on your own