The ATLAS detector - inside out

GK Student Lecture - 07.07.2014 – by Julia I. Hofmann

The Large Hadron Collider (LHC)

- located at CERN (near Geneva)
- circumference 26.7 km
- ca. 100 m underground
- 1232 superconducting dipoles à 14.3 m length: operational temperature: 1.9 K
- can provide collisions of protons on protons or heavy ions and heavy ion – heavy ion collisions
- hadron collider yields broad range of collision energies → good for discoveries
- 4 main experiments:
  - ALICE (mainly interested in heavy ion collisions)
  - ATLAS (multi purpose detector mainly interested in Higgs and new physics)
  - CMS (similar physics program like ATLAS, but different technologies: complementary, safety, competition)
  - LHCb (forward spectrometer: mainly interested in b-physics)

- particles are accelerated in a chain of accelerators:
  - most of them have/had own physics programs
  - LHC is the last one
- design centre-of-mass energy for proton-proton collisions: 14 TeV
- already delivered proton data at $\sqrt{s}$ = 2.76 TeV, 7 TeV and 8 TeV during years 2010 - 2012
- next run period foreseen for 2015 with $\sqrt{s}$ = 13 TeV
- particles are grouped in bunches that will collide
- up to 2835 x 2835 bunches possible
  - distance between bunches: 7.5 m ~ 25ns
  - bunch crossing rate: 40 MHz
- 10^{11} protons per bunch to maximise luminosity: Goal 10^{34} $cm^{-2}s^{-1}$

The ATLAS detector

- mainly built to search for Higgs boson and physics beyond the Standard Model
  - design goals set to get maximal sensitivity for these final states:
    - precise tracking to reject pile up and resolve secondary vertices
    - maximal coverage of the solid angle (4π not possible)
    - possibility to distinguish different particle species
      →different sub components each specialized in certain aspect of particle measurement
    - goal: measure jet energy to 1 % precision and lepton energy to 0.02 %
- offers possibility to study a range of interesting physics (see lecture 3)
- 44 m long and 25 m high

- weight ~ 7000 t
- multipurpose experiment: aims for complete recording of collision

The coordinate system

- right-handed coordinate system
- x-axis points towards the centre of the LHC
- y-axis points upwards
- z-axis points along the tunnel
- pseudo-rapidity of particles from the primary vertex is defined as $\eta = -\ln \tan(\theta/2)$ with θ being the polar angle of the particle direction measured from the positive z-axis
- transverse momentum / energy p_T / E_T: momentum / energy perpendicular to beam axis

Particle Detection

- detection of particles happens via their energy loss in the material it traverses
- energy loss can happen via different processes:
  - Charged particles: Ionization, Bremsstrahlung, Cherenkov ...
  - Hadrons: Nuclear interactions
  - Photons: Photo/Compton effect, pair production
  - Neutrinos: Weak interactions

Electrons

- energy loss mainly via bremsstrahlung: $-dE / dx = E / X_0$
- electron energy down to 1/e after passing through X_0 (Radiation length)

  → want only little material in front of calorimeters (trackers, solenoid)
  but more than 20 X_0 for EM calorimeter to fully contain shower
- examples: X_0/ρ for water 36 cm, for lead 0.56 cm, for steel 1.76 cm

Photons:

- mean free path for e+e− pair production from γ: 7/9 X_0

Hadrons:

- characteristic scale: nuclear interaction length λ
- relevant for total calorimeter depth (hadronic + electromagnetic)
- examples: λ/ρ for water 83.6 cm, for lead 17.1 cm, for steel 17 cm

Muons:

- basically heavy electrons: Radiation length much longer

Magnet system

- needed for momentum measurement of particles
- uses superconducting magnets
- central solenoid in front of calorimeters
  - 5.3 m long and has diameter of 2.4 m

    - B ~ 2 T magnetic field for inner detector
    - only 0.66 radiation lengths X_0 thick
    - made from aluminium enforced Nb/Ti conductor
    - operation temperature 4.5 K
- 3 toroids:
    - 1 barrel toroid made from 8 air core coils and Nb/Ti/Cu conductor
    - 2 endcap toroids mounted within the barrel toroid and having similar setup like the former
    - B ~ 1 T
    - operation temperature 4.6 K
- magnetic field constantly monitored by 1800 Hall sensors

<u>Inner Detector</u>

- detection principle: ionisation → only charged particles can be measured
- yields precise position measurement needed for
    - reconstruction of primary vertex (vertex with highest p_T in collision)
    - reconstruction of secondary vertices from long lived particles (e.g. B mesons)
    - signal matching (e.g. track-cluster matching)
- needs to have low material budget to minimise multiple scattering
- technology needs to be radiation hard, as close to beam pipe
- has 3 sub components: **Pixel** detector, **S**emi**C**onductor **T**racker and **T**ransition **R**adiation **T**racker
- Pixel and SCT are semiconducting detectors:
    - semiconductors can have different sizes: small pixels or larger structures (e.g. strips) depending on spacial resolution needed
    - charged particles traversing depletion region of semiconductor ionize material creating a pulse which can be read out
- basic principle of tracking:
    - use multiple layers of location sensitive detectors
    - reconstruct trajectory of particle
    - additional use of magnetic field allows momentum and charge measurement
    - the higher the momentum of a particle, the less bent will be its track
      → harder to measure
    - experimental challenges: noisy and dead tracking channels
      → sophisticated tracking algorithms have to be used to account for this
- charged track (p_T ~ 10 GeV) in central (barrel) region of ATLAS passes through:
    - beryllium beam pipe
    - 3 pixel layers
    - 4 double SCT layers
    - ~ 36 TRT straws

Pixel Detector:

- high granular pixel detector close to interaction vertex in order to reject pileup
- 3 barrel layers & 3 end discs
- n-type Si-semiconductor
- size: 50 x 400 μm^2
- position resolution: 10 x 155 μm^2

- allows to distinguish particles not coming from primary vertex (no hit in innermost layer)
- operating temperature between -5°C and -10°C

SemiConductor Tracker:

- similar technology like pixel detector, but semiconductor segmented in 6.4 cm long stripes
- adding additional pixel layers would cost:
  - money
  - more channels to be read out → complexity, event size (storage)
  - material budget: Pixel readout on device, SCT read out on ends

  → now come coarser structures
- 4 cylindrical layers & 9 end discs
- each layer consists of two strip layers slightly tilted against each other to improve position resolution: 17 x 580 µm²
- operating temperature between -5°C and -10°C

Transition Radiation Tracker:

- consists of 4mm thick straw tubes filled with $Xe/CO_2/O_2$ gas with anode in the middle
- extends tracking information up to ~ 1m from interaction vertex
- transition radiation allows to distinguish electrons from pions
  - transition radiation occurs if relativist particle passes boundary between two media with different refraction indices
  - in TRT realised through polyprohylene foam
  - pions are heavier than electrons → their transition radiation is energetically lower
- barrel: 73 layers of straw tubes up to 144 m long
- end caps 160 layers of straw tubes
- operates at room temperature

<u>Calorimeters</u>

- ATLAS has two types of Calorimeters: The electromagnetic (EM) and the hadronic calorimeter
- needed for different particle species (leptons vs. hadrons) as mechanism of energy deposition is different
- Calorimeters measure energy →particle needs to be stopped completely
- Measurement relies showering of particles (cascade production of particles)
  - Hadronic showers are deeper than EM ones due to nuclear interactions
  - Hadronic showers are less uniform than EM showers due to many possible final states
    - → hadronic calorimeter bigger than EM calorimter and segmentation in depth helps to distinguish electrons form hadrons (jets)
- ATLAS uses so called sampling calorimeters: alternating layers of absorber and active material
  - absorber materials need to have high density; e.g. Iron, Lead, Uranium
  - active materials will be read out; e.g. Plastic scintillators, liquid ionisation chamber, gas detector
  - passive material worsens the energy resolution, but allows for compacter and cheaper calorimeters
- Energy measured in calorimeter cells: Fine granularity helps distinguish prompt photons and photons from e.g. π^0 decay, but requires more readout

- Transverse energy imbalance E_T^{miss} indicates particles that escaped without detection (e.g. neutrinos)
- E_T^{miss} computed by summing all energy deposits from calibrated objects vectorially, adding muons and unmatched calorimeter clusters

The electromagnetic Calorimeter:
- outside the solenoid
- segmented into barrel and forward region
- accordion shaped absorber plates made from lead – advantage: no gaps in φ direction
- electrodes made from Kapton (high voltage readout ~ 2kV)
- active material: liquid argon
- 3 sampling layers in radial direction with thickness 4.3 X_0, 16 X_0 and 2X_0
- granularity in second layer: $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$

The hadronic Calorimeter:
- segmented into barrel and extended barrel
- steal absorber plates
- active material: tile shaped plastic szintillators (polysteren)
  - readout via optic fibres
- 3 sampling layers in radial direction with thickness 1.5 λ, 4.1 λ and 1.8 λ
- granularity in first two layers: $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

The Muon System

- muons not stopped in calorimeter → need dedicated detector for measurement
- measurement principle: ionisation
- standalone system → can even work without rest of ATLAS
- barrel embedded in the toroid magnets has 3 layers of detection chambers
- forward region: 2 wheels
- 4 different detector types:
  - 2 for triggering: resistive plate chambers and thin gap champers
  - 2 for momentum measurement:
    - monitored drift tubes:
      - several layers of drift tubes with 30 mm diameter and filled with Argon and CO_2
    - cathode strip chambers
      - also filled with Argon and CO_2

Sources:

1. The ATLAS Experiment at the CERN Large Hadron Collider, *JINST* **3** S08003
2. Lectures of Hans-Christian Schultz-Coulon (http://www.kip.uni-heidelberg.de/~coulon/)
3. Lectures of Monica Dunford (http://results-lhc.physi.uni-heidelberg.de/Lectures/)