

Chapter 2

Overview of the ATLAS Experiment at the LHC

A brief description of the Large Hadron Collider (LHC) and the experiment ATLAS is presented in this chapter. The LHC design overview (Sect. 2.1) is followed by the short description of the ATLAS detector components (Sect. 2.2). Next, a brief summary of the particle physics theory is given and the main goals of the physics programme at the ATLAS experiment are mentioned (Sect. 2.3).

2.1 Large Hadron Collider

The LHC [1] at CERN was built to allow studies of the particle physics processes at high energy and luminosity conditions that have not been reached before. It was designed to collide proton beams at the centre of mass energy 14 TeV at a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. These conditions have not been reached by the end of 2011. After tests at lower energy, the LHC started its operation at 7 TeV centre of mass energy in spring 2010 and continued with the same energy during 2011. Total integrated luminosity delivered to the ATLAS experiment was 0.05 fb^{-1} in year 2010 and 5.61 fb^{-1} in 2011. The peak luminosity reached in ATLAS during 2011 running was $3.65 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Two general purpose detectors were built to explore the proton-proton and heavy ions collisions at the LHC—ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid). Since the measurements described in the thesis have been performed with the ATLAS detector, the ATLAS experiment is described in more details below.

2.2 ATLAS Detector

The design of the ATLAS detector was devised to allow a study of as wide range of physics processes as possible. Particularly, searches for so-far unobserved particles represent an experimental challenge and they define requirements for the ATLAS apparatus.

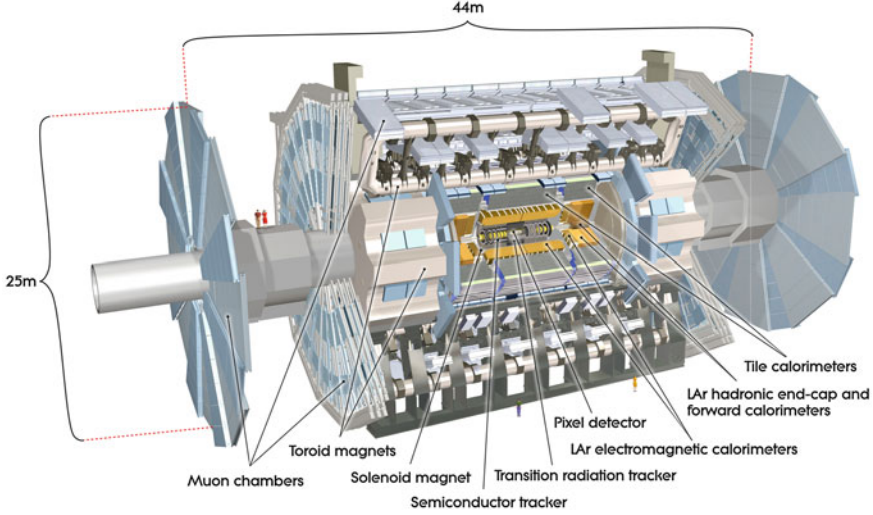


Fig. 2.1 Layout of the ATLAS detector [2]

The ATLAS detector and its expected performance are described in details in Ref. [2]. The detector contains several layers of different sub-detectors, namely the inner detector closest to the beam pipe, electromagnetic and hadronic calorimeters and muon chambers laying in the largest distance from the interaction point. The ATLAS detector design is formed also by magnets. The magnet configuration consists of the superconducting solenoid surrounding the inner detector and three large superconducting toroids (one barrel and two end-caps) arranged with an eight-fold azimuthal symmetry around the calorimeters. The layout of the ATLAS detector is shown in Fig. 2.1.

2.2.1 Coordinate System

The coordinate system used in this thesis follows the standard ATLAS definition [2] which is the following: The nominal interaction point is defined as the origin of the coordinate system, while the beam direction defines the z -axis and the x - y plane is transverse to the beam direction. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y -axis is defined as pointing upwards. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$. The transverse momentum p_T , the transverse energy E_T and the missing transverse energy E_T^{miss} are defined in the x - y plane.

The distance ΔR in the η - ϕ space is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

2.2.2 Inner Detector

The tracking detector is placed inside a 2 T magnetic field which is generated by the solenoid magnet surrounding the inner detector. It is designed to provide detailed information about charged particles, namely the transverse momentum and primary and secondary vertices are measured with the tracking detector. The inner detector is built of a number of individual components as shown in Fig. 2.2.

The precision pixel and silicon microstrip (SCT) trackers with a very fine segmentation cover the pseudorapidity range up to $|\eta| < 2.5$. The precision tracking detectors are arranged on concentric cylinders around the beam axis while in the end-caps they are located on disks perpendicular to the beam axis. The first layer of the pixel detector with highest granularity, so-called B-layer, is very important for an excellent vertexing. Typically three pixel layers and eight SCT layers are crossed by a good quality track.

A large number of hits, typically 36 per track, is measured with straw tubes of the Transition Radiation Tracker (TRT) which covers the pseudorapidity region up to $|\eta| < 2.0$ and creates the outermost part of the tracking detector. The TRT detector enables also the electron vs. pion identification through the detection of transition radiation photons in the xenon-based gas mixture of its straw tubes.

The tracking system has an expected resolution of $\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$ (with p_T in GeV) in the whole pseudorapidity coverage $|\eta| < 2.5$ [2].

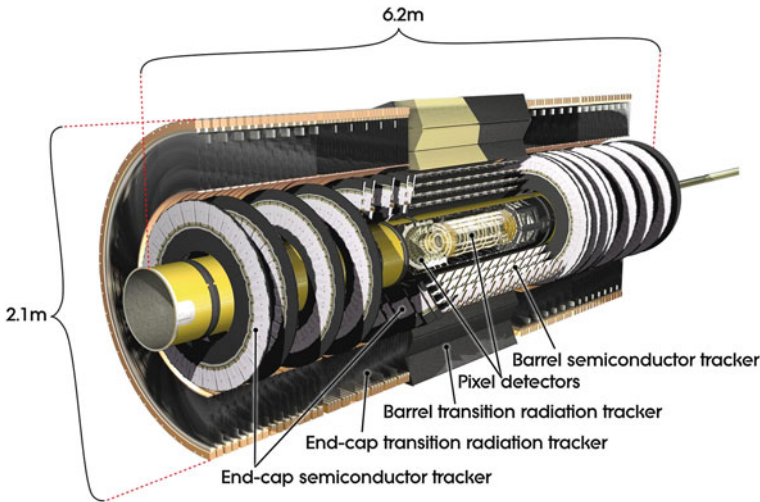


Fig. 2.2 Components of the ATLAS inner detector [2]

2.2.3 Calorimeters

The ATLAS calorimetry system, shown in Fig. 2.3, consists of different types of sampling calorimeters covering the total pseudorapidity range $|\eta| < 4.9$. The fine granularity of the electromagnetic calorimeter in the region matched to the inner detector is necessary for precision measurements of electrons and photons. The hadronic calorimeters are dedicated for the jet reconstruction and missing transverse energy measurement for which a coarser granularity is sufficient.

The electromagnetic (EM) system consists of two parts—a presampler and an EM calorimeter. The EM calorimeter with the liquid argon (LAr) as an active material has a typical structure of an accordion-geometry with kapton electrodes and lead absorber plates. The calorimeter is symmetric in the azimuthal angle without any azimuthal cracks. The calorimeter is built of three longitudinal layers. Most of the EM shower energy for high E_T electrons and photons is collected in the middle layer which has a fine granularity of 0.025×0.025 in $\eta \times \phi$ space. The first layer, so-called strip layer, offers an excellent $\gamma - \pi^0$ discrimination. The last layer with coarser granularity collects the energy deposited in the tail of the very energetic EM showers. The EM calorimeter is divided into a barrel part ($|\eta| < 1.475$) and two end-caps ($1.375 < |\eta| < 3.2$). The presampler detector is located in front of the EM calorimeter in the region $|\eta| < 1.8$. It is developed to correct for the energy lost in the material before the calorimeter. It consists of an active LAr layer of thickness 1.1 cm in the barrel and 0.5 cm in the end-cap.

The Tile Calorimeter is a hadronic calorimeter covering the range $|\eta| < 1.7$ with steel used as an absorber and scintillating tiles as an active material. The design of the

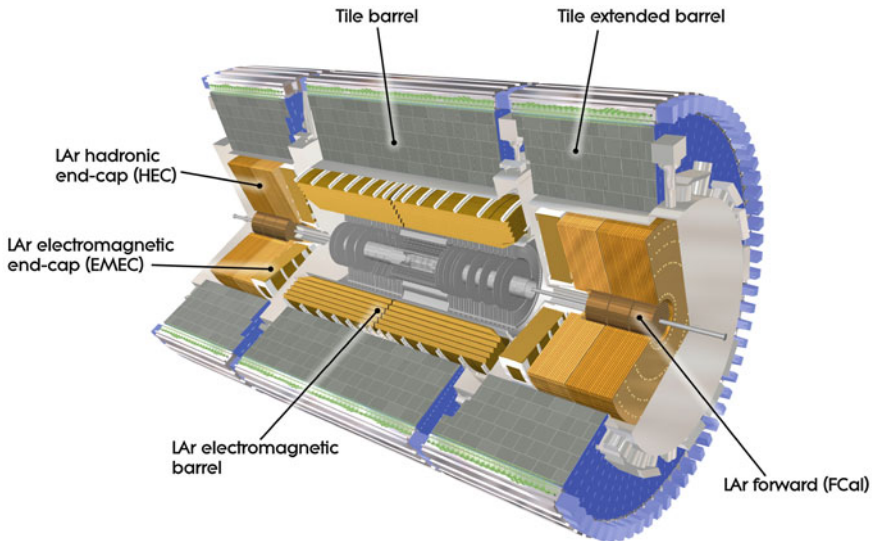


Fig. 2.3 Calorimetric system of the ATLAS detector [2]

Tile Calorimeter is described in details in Chap. 3. Contrary to the Tile Calorimeter, the forward hadronic calorimeters use the LAr technology. The Hadronic End-cap Calorimeter (HEC) covers pseudorapidity range from 1.5 to 3.2 using copper as the absorber. Finally, the Forward Calorimeter (FCal) covers the most forward region up to $|\eta| < 4.9$. The FCal consists of three modules in each end-cap: The first module is made of copper and is optimised for electromagnetic measurements, the other two are made of tungsten and are used primarily for measurements of the hadronic showers.

The designed resolution of the calorimetric system is the following (with E in GeV) [2]:

- Electromagnetic calorimeter ($|\eta| < 3.2$): $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Hadronic calorimeter (jets):
 - Barrel and end-cap ($|\eta| < 3.2$): $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
 - Forward region ($3.1 < |\eta| < 4.9$): $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$.

2.2.4 Muon System

The muon spectrometer measures the deflection of the muon tracks in the magnetic field produced by large superconduction air-core toroid magnets (one in the barrel and two in the end-caps) in the region $|\eta| < 2.7$. The spectrometer chambers are arranged in three cylindrical layers around the beam axis while in the transition region and in the end-caps the chambers are installed in three planes perpendicular to the beam axis. The layout of the muon chambers is shown in Fig. 2.4.

The Monitored Drift Tubes (MDTs) cover most of the pseudorapidity range of the muon system and provide a precision measurement of the muon tracks. Cathode Strip Chambers (CSCs) with higher granularity are used in the large pseudorapidities ($2.0 < |\eta| < 2.7$). The CSCs are radiation resistant and can be used in a region with an increasing particle rate.

The muon trigger system covers the pseudorapidity range up to 2.4. Resistive Plate Chambers (RPCs) are used in the barrel and Thin Gap Chambers (TGCs) in the end-caps. These chambers are used to measure the muon coordinate in the direction orthogonal to the precision-tracking chambers and also for triggering.

The expected resolution of the muon spectrometer is $\sigma_{p_T}/p_T = 10\%$ at $p_T = 1$ TeV [2].

2.2.5 Forward Detectors

The forward region of the pseudorapidity is covered with three smaller detectors—LUCID, ALFA and ZDC.

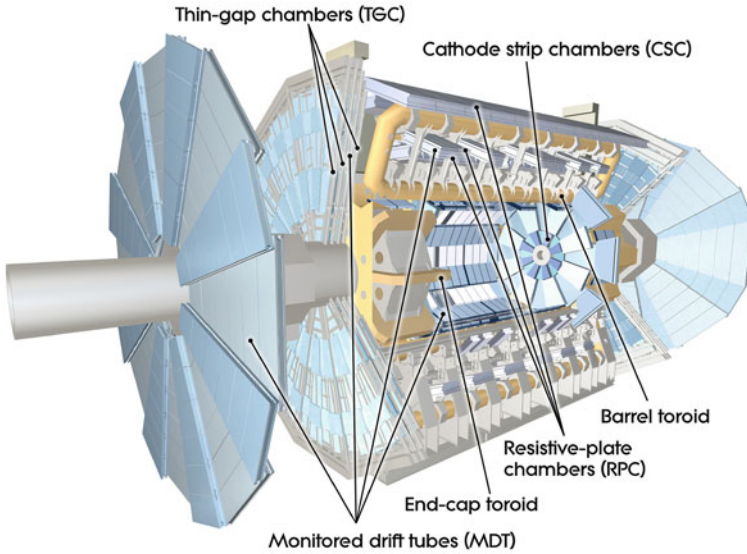


Fig. 2.4 Muon system of the ATLAS detector [2]

The main goal of LUCID (LUMinosity measurement using Cerenkov Integrating Detector) and ALFA (Absolute Luminosity For ATLAS) is a measurement of the luminosity delivered to ATLAS. LUCID is located at ± 17 m from the interaction point and provides online relative luminosity for ATLAS. ALFA is located at ± 240 m and is made of scintillating fibre trackers located inside Roman pots. ALFA is optimised for measuring the absolute value of the delivered luminosity.

The third component of the forward system is called ZDC (Zero-Degree Calorimeter) and is designed to measure the production of neutral particles in the very forward direction ($|\eta| > 8.2$).

2.2.6 Trigger

The collision rate at the design luminosity will be 40 GHz and the final rate of events being saved after the trigger decision might reach 400 Hz maximum. The trigger system in ATLAS consists of three distinct levels: Level 1 (L1), Level 2 (L2) and Event Filter (EF).

The L1 trigger reduces the rate to about 75 kHz and it has to provide the decision within less than $2.5 \mu\text{s}$. The L1 trigger searches for high momentum muons, electrons, photons, jets, hadronically decaying τ leptons as well as large missing transverse energy and total transverse energy. It can access only limited information from calorimeters and muon chambers. The L1 trigger defines so-called regions of interest (RoIs)—coordinates in η and ϕ where a high energy object might be located.

The L2 trigger starts from the RoIs provided by L1. Full granularity and precision is available for these regions at L2 stage. The L2 trigger has the average event processing time of about 40 ms and it is designed to reduce the trigger rate down to 3 kHz.

In the last step, the EF trigger reduces the event rate to approximately 200–400 Hz. The EF can access the full information from the whole detector and it uses some of the offline analysis algorithms within the average event processing time of about 4 s.

2.3 Physics Programme at the ATLAS Experiment

A short description of the particle physics theory is presented, followed by highlights of physics measurements at the ATLAS experiment in this section.

2.3.1 Theoretical Introduction

Interactions between fundamental components of the matter are described by Standard Model which is a quantum field theory based on $SU(3) \times SU(2) \times U(1)$ symmetry group. The interactions between the constituents of the matter (spin 1/2 fermions) are described by an exchange of intermediate bosons with spin 1.

The quantum chromodynamic (QCD) [3] is an $SU(3)$ gauge theory where the colour charge defines the local symmetry. The interactions between quarks, which form a triplet under colour $SU(3)$, are mediated by the exchange of gluons. The eight gluons carry the colour charge and therefore are self-interacting. Unlike the electromagnetic interaction, the strong interaction strength is small for large momentum transfers (asymptotic freedom) and large for small momentum transfers (confinement). The confinement gives an explanation why the quarks form colour neutral hadrons and cannot be observed individually.

The electroweak interactions [4] are described by an $SU(2) \times U(1)$ symmetry group. Left-handed leptons and quarks form doublets under $SU(2)$, while the right-handed states are singlets. Four intermediate bosons appear in the electroweak theory—a photon, Z and $W^\pm$ bosons. One of the crucial differences between the photon and the Z and $W^\pm$ bosons is that the photon is massless while the weak interaction bosons are very heavy. The mass terms of the intermediate bosons can be introduced in the Standard Model by spontaneous breaking of the $SU(2) \times U(1)$ symmetry, so-called Higgs mechanism. The simplest way is to consider an $SU(2)$ doublet of complex scalar fields where three degrees of freedom are absorbed in the mass terms of the Z and $W^\pm$ bosons and the remaining degree of freedom results in the physical state—the Higgs boson. The Higgs mechanism has not been confirmed experimentally yet. It has been one of the main goals of the ATLAS experiment to find the Higgs boson particle if it exists.

Despite the fact that the Standard Model describes well the experimental data, the model has several theoretical shortcomings (e.g. fine tuning of the Standard Model parameters, large number of free parameters, no candidate for dark matter) and therefore it is not expected to be the final model. Based on the excellent agreement with the experiment, the new model must obtain the Standard Model theory in the limit of low energy. One of the possible extensions of the Standard Model is the Supersymmetry [5] where a supersymmetric partner is assigned to each Standard Model particle—bosonic partners (squarks and sleptons) to fermions and fermionic partners (gluinos and gauginos) to bosons. In the minimal supersymmetric extension of the Standard Model (MSSM) the Higgs boson sector contains five physical states - two scalars (h , H), one pseudoscalar (A) and two charged Higgs bosons ($H^\pm$). Apart from Supersymmetry, also other alternative theories to the Standard Model exist, e.g. technicolour. No particle beyond the Standard Model has been observed experimentally yet and it is a challenge for the ATLAS experiment to find a signature of the physics beyond the Standard Model.

2.3.2 Physics Measurements at the ATLAS Experiment

The physics programme at the ATLAS experiment [5] can be divided into two main parts - precision measurements of the Standard Model properties and searches for not yet observed particles (Higgs boson and particles beyond the Standard Model). The Standard Model measurements and the Higgs boson searches are briefly discussed below.

Standard Model Measurements

The Standard Model measurements play an important role for several reasons. First of all, the Standard Model processes represent the main background for the signatures of the new physics. Therefore an excellent understanding of the Standard Model background is very crucial. Moreover, the well-known processes such as decays of W and Z bosons to leptons are used as a standard candle to calibrate the detector and to correct the Monte Carlo simulations to agree with measurements using real data samples (e.g. smearing of the lepton energy/momentum, correcting efficiency predictions in simulations). This process is illustrated in Chap. 4. Next, precision measurements of the Standard Model parameters can be performed at the ATLAS experiment (e.g. triple gauge boson couplings in diboson final states, W boson mass). Finally, deviations from the Standard Model predictions might indicate physics beyond the Standard Model (e.g. deviations in the high- p_T spectrum of dijet events might be a sign of quark compositeness).

The top quark physics is an important part of the Standard Model programme at the ATLAS experiment. Precise measurements of the top mass as well as other top

quark properties (e.g. charge) are performed with the ATLAS detector. The single top production cross section is also being measured.

Besides the high energy physics, also B -physics measurements are performed at ATLAS experiment. The specific B -physics topics include the measurement of CP violation, B_s^0 mixing and a search for rare decays. Study of B hadrons' decays and spectroscopy is also a part of the B -physics programme.

Higgs Boson Searches

The search for the Higgs boson particle is one of the main goals of the ATLAS experiment. The Higgs boson is predicted by the Standard Model, however its mass is a free parameter. Due to theoretical constraints, the Higgs boson mass must be lower than approximately 800 GeV [6]. The direct search at LEP excluded the Higgs boson with the mass lower than 114.5 GeV at 95 % confidence level (CL) [7].

The Higgs boson searches have been performed by ATLAS and CMS experiments at the LHC. Both experiments announced an observation of a new particle which could be the Higgs boson particle in July 2012. The results are published in Ref. [8], resp. [9] for the ATLAS, resp. CMS experiment. The properties of the observed particle are compatible with the Standard Model Higgs boson, but more data are needed to confirm this hypothesis. The observed Higgs-like particle has a mass of approximately 125 GeV.

The most important Higgs boson decay modes used in ATLAS in the mass region of the new Higgs-like particle are:

- $H \rightarrow \gamma\gamma$ Although the branching ratio of this channel is very low ($\text{BR} \approx 0.2\%$), it provides the best sensitivity in the low mass region. A very good photon identification, robust against multijets that might be possibly faking photons, as well as an excellent energy reconstruction are the key ingredients for the measurement in this channel. The diphoton invariant mass spectrum is used as the discriminating variable. More details about the observation of the Higgs-like boson in this channel can be found in Ref. [10].
- $H \rightarrow ZZ \rightarrow 4\ell$ This channel would give the cleanest signal in the intermediate Higgs boson mass range. However, the branching ratio below 150 GeV decreases rapidly and it is more difficult to use this channel also in the low mass range. Two pairs of isolated leptons with same flavour and opposite charges are searched for. The invariant mass of the four leptons' system is considered as the discriminant. A high efficiency of the lepton trigger and lepton identification as well as a very good energy resolution are required for the precise measurement in this decay mode. Details about the measurement of the properties of the Higgs-like particle in this channel can be found in Ref. [11].
- $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ The decay mode with two W bosons leads to the best sensitivity in the intermediate Higgs boson mass range and it can also contribute in the lowest Higgs boson mass range. The typical signature is formed by a pair of isolated leptons with opposite charges and large missing transverse energy. The

invariant mass cannot be reconstructed and therefore the transverse mass of the Higgs boson is used as the discriminant. The recent analysis in this channel using full 2011 and 2012 datasets is described in Ref. [12].

- $H \rightarrow \tau\tau$ The Higgs decay mode with a pair of τ leptons is measurable in the low mass region. The difficulty of the search in this channel comes from the hadronic τ which might appear in the final state as a jet can be easily misidentified as a hadronic τ . Therefore the large multijet background must be carefully taken under control. The invariant mass of the Higgs boson cannot be directly reconstructed due to neutrinos from the τ leptons' decays. Alternative mass reconstruction technique, so-called Missing Mass Calculator [13], is used in this channel. The $Z \rightarrow \tau\tau$ process, studied in this thesis, forms the dominant background. Thus a good understanding and description of this background is crucial for the $H \rightarrow \tau\tau$ analysis. The Higgs-like particle has not been observed in this channel by the ATLAS experiment yet. It is an important decay mode which could confirm that the Higgs boson decays into a pair of fermions. The analysis using full 2011 data and a part of 2012 data corresponding to $4.7 \text{ fb}^{-1} + 13.0 \text{ fb}^{-1}$ is described in Ref. [14].
- $H \rightarrow b\bar{b}$ This is the decay mode with the largest branching ratio in the low mass region, however very difficult to detect over the overwhelming multijet background. It can be performed only in the associated production of the Higgs boson with electroweak bosons (ZH , WH) or with a top quark pair ($t\bar{t}H$). The Higgs-like particle has not been observed in this channel yet. More details about the analysis can be found in Ref. [15].

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Standard Model Measurements with the ATLAS Detector
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