ATLAS muon reconstruction from a C++ perspective: a road to the Higgs
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CHAPTER 2  The ATLAS Experiment

*Man shall never reach the moon, for such a quantity of gunpowder would be needed as to gravely injure the crew.*

*Children’s Encyclopaedia, 1926*

2.1 The LHC

Of the colliders currently in operation at CERN\(^1\), the electron-positron collider LEP achieves the highest centre-of-mass energy, surpassing the 200 GeV. During its lifetime it has undergone many upgrades, but increasing its energy into the TeV range will not be possible. For a circular collider like LEP, the energy loss due to bremsstrahlung would become too high: a 500 GeV electron would come virtually to a halt before it would have been able to make one full turn through the accelerator. The only way to accelerate electrons to these kinds of energies is to use a linear collider.

However, because of the infrastructure available at CERN (see figure 2.1), a circular collider is a much more viable option. The only solution then is to use heavier particles. Because the amount of synchrotron radiation is inversely proportional to a particle’s mass to the fourth power, a proton would generate only a fraction of the radiation lost by an electron. CERN has therefore decided to build the Large Hadron Collider or LHC, a proton-proton collider that will replace LEP and become operational in 2005 [11].

![CERN accelerators diagram](image)

**Figure 2.1** CERN accelerators.

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1. The European Laboratory for Particle Physics, located near Geneva, Switzerland.
The disadvantage of using protons is that they are not elementary particles; they consist of three valence quarks and a sea of quark and anti-quark pairs, all immersed in a plethora of gluons. All of these constituents carry part of the proton's energy, and it is these particles that actually collide with each other. As a result, to create collisions with energies around 1 TeV, the protons have to be accelerated to much higher energies. This has led CERN to set the centre-of-mass energy of the LHC at 14 TeV.

Another unfortunate side effect of all these particles within the proton is that most of the collisions will have a soft hadronic nature, and will do nothing more than to obscure the interesting events. The interesting cross sections are consequently small, and in order to be able to maintain an effective physics programme, the interaction rate must be immense. The LHC will concentrate the protons into bunches, each containing around 100 billion particles. When the two bundles are then focused on each other, an average of 23 collisions will take place at each bunch crossing. The majority of these are of a soft hadronic nature and are called minimum bias events or "pile-up". Together with a 25 ns bunch spacing, this means that the LHC will operate at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$.

To study the collisions at the interaction points of the LHC, two general-purpose particle detectors are being built: ATLAS (A Toroidal LHC Apparatus [12, 13]) and CMS (Compact Muon Solenoid [14]).

### 2.2 The ATLAS Detector

ATLAS is a general-purpose detector, not only capable of finding the Higgs in the mass range from 80 GeV to 1 TeV, but also versatile enough to study B and top physics, supersymmetry, heavy vector bosons, and many other topics. As any typical colliding-beam detector it consists of an inner and outer tracker separated by electromagnetic and hadronic calorimeters (see figure 2.2).

**Inner Detector**

The inner detector utilizes three technologically different subdetectors to measure charged particles and to identify (secondary) vertices. Closest to the interaction point are layers of high-resolution pixel detectors, which provide 3-dimensional space points essential for the vertex reconstruction. On the outside of it lie the layers of the silicon strip detector (SCT), followed by the TRT, a straw tube transition radiation tracker. To reconstruct the particles' momenta, the whole inner tracker is surrounded by a superconducting solenoid generating a field with an average value of 2 Tesla.

**Calorimetry**

The ATLAS calorimetry uses different techniques in various regions of the detector as best suited to the specific requirements and the varying radiation environment. The electromagnetic calorimeter is a liquid-argon (LAr) detector with an accordion geometry. In the range $|\eta| < 1.8$...
it is preceded by a presampler, whose finer granularity can be used to discriminate between photons and pions.

The hadronic calorimeters in the barrel are made of iron interspersed with scintillating tiles directed towards the interaction point. In the endcaps the tiles are not suited because of the high levels of radiation present there, and are replaced by liquid argon calorimeters. They extend the coverage up to a pseudorapidity of $|\eta| = 4.9$, which is needed to correctly identify events with missing energy.

**Outer Tracker**

The calorimeter is surrounded by the muon spectrometer, a tracker that is based on large superconducting air-core toroids (see the next section). It defines the overall dimensions of the ATLAS detector: The outer chambers of the barrel are at a radius of about 11 m, the half-length of the barrel toroid coils is 12.5 m, and the third and outer layer of the forward muon chambers, mounted on the cavern wall, is located some 23 meters from the interaction point.
2.3 The Muon Spectrometer

The muon spectrometer consists of widely interspersed stations of chambers, which are positioned in such a way that particles coming from the interaction point always traverse at least three of them. In the barrel region this is achieved by arranging them in cylindrical layers around the beam axis, while in each endcap wheels with detectors, concentric around the beam axis are used (see figures 2.3 and 2.4). In both these regions the detector is divided into 16 towers alternately consisting of large and small stations.

Each station contains one chamber for the precision measurement of the particle’s position. In most cases these are MDTs (Monitored Drift Tube chambers), and only in the inner forward region where the counting rate is extremely high are they replaced by Cathode Strip Chambers (CSCs). Some stations also contain separate trigger chambers: Resistive Plate Chambers (RPCs) in the barrel and Thin Gap Chambers (TGCS) in the endcaps. Together they contain a total number of readout channels exceeding the 1.2 million.
Figure 2.4 Side view (rz-projection) of one quadrant of the muon spectrometer.

Magnetic Field

The measurement of the particles’ momenta is made possible by the presence of a toroidal magnetic field. This field is generated by 3 superconducting air-core magnets whose coils follow an eight-fold symmetry, with the endcap toroids rotated with respect to the barrel ones by 22.5° (see figure 2.3).

The open structure of the magnets minimizes the effects of multiple scattering and energy loss. In the barrel it allows for the reconstruction of a muon’s momentum from a measurement of the sagitta in the three muon stations. In the endcaps the positions of the magnet cryostats do not allow for this arrangement. Instead, the muon momenta are obtained from a point-angle measurement with one point in front of and two points behind the magnetic field region.

The open air-core toroid generates a relatively modest magnetic field with an average value of 0.5 Tesla. A field that is also very inhomogeneous (see e.g. figure 2.5) so that particle trajectories can be very irregular, especially at low transverse momenta.

Figure 2.5 Field integral versus $\eta$ for infinite momentum muons. Each curve corresponds to a fixed azimuthal angle [15].
**Precision Chambers**

Monitored drift tubes are used for the precision measurement over most of the area of the detector. Almost all MDT chambers consist of two multilayers made up of 3 or 4 monolayers of drift tubes. The barrel chambers are rectangular while the endcap chambers are of trapezoidal shape, but otherwise the design is similar.

The aluminium drift tubes have a diameter of 30 mm and are operated with a gas mixture Ar(91%)-N$_2$(4%)-CH$_4$(5%) at 3 bar absolute pressure. With the selected gas, the maximum drift time is around 500 ns and the average single tube resolution is 80 micron, except very close to the wire where it rises sharply.

Only in the inner station of the endcap region are the MDTs replaced by cathode strip chambers to provide a finer granularity, which is required to cope with the demanding rate and background conditions present there. CSCs are multiwire proportional chambers with cathode strip readout. They have a symmetric cell in which the anode-cathode distance is equal to the anode wire spacing, viz. 2.54 mm. This is considerably less than the MDT tube radius, thereby lowering the occupancy per wire as well as the electron drift times to a maximum of 30 ns. The precision coordinate is obtained from a measurement of the charge induced on the segmented cathode by the avalanche formed on the anode wire. The resulting resolution is around 60 μm.

**Trigger**

The muon trigger chambers cover the pseudorapidity range of $|\eta| \leq 2.5$ and serve a threefold purpose:

- First and foremost as a trigger system with a well-defined $p_T$ cut-off. This requires a granularity of the order of 1 cm, given the magnetic field generated by the toroids.
- For bunch crossing identification, requiring a time resolution better than the LHC bunch spacing of 25 ns.
- For the measurement of the second coordinate, i.e. the coordinate in the direction orthogonal to the one measured in the precision chambers, with a typical resolution of 5-10 mm.

In the barrel, the trigger chambers in the form of the RPCs are arranged in three layers. They are located on both sides of the middle MDT station and either directly above or below the outer MDT station (see figure 2.3). The RPCs are gaseous detectors providing a typical spatial resolution of 1 cm and a time resolution of 1 ns. The basic unit is a narrow gas gap formed by two parallel resistive plates with readout strips on both sides of the gap, one measuring the $\eta$- and the other the $\phi$-coordinate. Each chamber then consists of two such units.
The TGCs form the trigger system in the endcaps. Three layers complement the middle MDT station while a fourth layer is present near the inner station, but that one is not used for the generation of the trigger signals. The TGCs are multiwire proportional chambers with the anode wires arranged parallel to the MDT wires. The two outermost chambers are doublets: They consist of two gas gaps, each equipped with readout strips that are orthogonal to the wires and that measure the second coordinate. The chambers on the inside of the middle MDT layer (TGC1 in figure 2.7) are triplets with three wire planes but only two strip planes. Finally, the TGC0 chambers, which are the ones closest to the interaction point, serve only to measure the second coordinate. They consist of two gas gaps without any strips.

The trigger system has been designed such that it can supply both low (6 GeV) and high (20 GeV) momentum trigger signals. The 6 GeV trigger in the barrel is based on the RPC1 and RPC2 layers. In both the $\eta$- and $\phi$-projection, a coincidence in 3 out of the 4 strip planes is required. In the endcaps, the same trigger is realised by a 3 out of 4 coincidence in the TGC2 and TGC3 chambers, i.e. the two outermost layers.

Both triggers can be extended to become 20 GeV triggers by respectively requiring an additional hit in each projection in the outer RPC layer, or a 2/3 coincidence in the bending plane of the triplet of wire layers of the TGC1 chambers plus a 1 out of 2 coincidence in its azimuthal strip planes.

2.4 ATLAS Computing

The ATLAS detector as described above is a complicated piece of equipment and as such requires a substantial effort to design, build and test it. This not only holds true for its hardware, but for its software as well. Most of the simulation, reconstruction and analysis software that is currently available is written in Fortran. However, due to the size and complexity of the code, this has led to severe maintenance problems. To solve these problems, ATLAS has after extensive studies [16-18] decided to adopt the object-oriented (OO) methodology, together with C++ as the implementation language [19-23].

2.4.1 Object Orientation

Object-oriented programming is about capturing the behaviour of the real world in a way that hides the implementation details. In other words, it allows the programmer to think in terms of the problem domain, as opposed to the world of the computer (language). It is also a data-centered view of programming in which data and behaviour are strongly linked: They are
combined into a single entity called a class. Instances of a class are called objects and each object has its own set of data, giving it a unique identity.

The three core features of OO are abstraction, encapsulation and polymorphism.

**Encapsulation**

Encapsulation, which is also referred to as data-hiding, is about hiding an object’s implementation, i.e. its data, from its clients. Instead, they only see the object’s interface, i.e. the behaviour it presents to the world. The advantage of this clear separation is that the object is free to implement its interface in any way it sees fit.

This feature can also be extended to entire software packages by limiting their entry points to a number of interface classes. Encapsulation can therefore lead to a significant reduction in the complexity of the software by increasing code modularity. It also enhances its flexibility and robustness, and promotes code reuse.

**Polymorphism & Inheritance**

Polymorphism allows different kinds of objects that share some common behaviour, i.e. have a common interface, to be used interchangeably. Or in other words, it is the ability of an operation to behave differently depending on the type of the object on which it is invoked. For example, a box and a tube are both geometrical objects that can be drawn on a screen, but the implementation of their `draw` method is completely different.

The way in which most object-oriented languages implement polymorphism is through inheritance. Inheritance can open the way to code reuse, but only when the class hierarchies are explicitly designed with that in mind.

**Abstraction**

Abstraction lies at the heart of OO: During the analysis phase, real world concepts are abstracted into classes. Later on, during the design, similarities among objects are expressed in terms of interfaces and base classes, using respectively polymorphism and inheritance.

When taking all this into account, an object-oriented application is simply a collection of collaborating objects: They interact and communicate with each other by sending and receiving messages. Whereas procedural designs rely heavily on a (few) main function(s) to manage the application, OO designs grant more equality of control to the objects within the application. The goal in OO design is to achieve a consistent set of objects whose behavioural characteristics (their interfaces) form the collaborations needed to fulfil the requirements.
2.4.2 Domain Decomposition

It was realised from the start that applying the object-oriented paradigm alone would not be sufficient to create high quality and maintainable software. A software process [24] was therefore developed, providing guidelines for the analysis, design and coding phases, and defining a review mechanism to check the quality of their outputs.

Part of the process has been the division of the software and its development into domains, the ones most important to the reconstruction being (see figure 2.8) [25]:

- The control domain provides the steering mechanisms for the application, i.e. the way domains communicate with each other, the method in which parameters from e.g. the user interface are made available, etc.;

- The (graphical) user interface provides access to the program and handles the user’s input. The design must be able to deal with the simultaneous existence of multiple interfaces;

- The event display represents visually the objects that exist within the ATLAS software. To meet the needs of the community, many different displays are envisaged;

\[\text{Figure 2.8 Domain decomposition of the ATLAS reconstruction software. The notation is explained in appendix A.1.1.}\]
- The **reconstruction** domain coordinates the activities of the detector domains, and performs the combined reconstruction and possibly the particle identification;

- The **inner detector, calorimetry** and **muon system** domains are responsible for the stand-alone reconstruction in the respective subdetectors;

- The **detector description** stores the description of the ATLAS detector in a database and makes it available through various logical views as needed by e.g. the simulation, the reconstruction and the event display;

- An **event** is the container for all data associated with a physics event, i.e. the raw or simulated data, the reconstruction results and the analysis objects. The event domain is responsible for the storing of these events, and for providing fast, flexible and easy access to them;

- The **magnetic field** domain provides access to the magnetic field, and performs the propagation of particles through it.

![Figure 2.9 Arve display and console window.](image)
2.4.3 Arve

As the baseline for further development of a full OO reconstruction program, Arve (the ATLAS reconstruction and visualization environment) has been adopted [26]. Arve is an object-oriented framework for reconstruction and physics analysis intended to facilitate fast and easy development. It defines the classes for building a detector hierarchy, and for simulating the traversal of particles through it. In addition, it defines a control and GUI structure with integrated graphics that are tailored towards the task of software creation.

This concludes the analysis of the problem domain. The next chapter continues with the design of the software.