Chapter 4

Reconstruction and Commissioning

This chapter describes basic particle reconstruction and identification. The types of commissioning activities required to understand the detector and the performance of the particle reconstruction algorithms, are introduced. Several related concepts used throughout the thesis are also presented. The following chapters expand on the topics introduced here. Chapters 5 and 6 go into detail about a particular aspect of commissioning: detector alignment. Chapter 7 describes the details of electron reconstruction and identification.

The remainder of the chapter is organized as follows: Section 4.1 describes basic particle reconstruction and identification. Section 4.2 introduces the concept of triggering and discusses related issues. Section 4.3 describes pile-up. Section 4.4 introduces the detector commissioning.

4.1 Particle Reconstruction

Particle reconstruction, or simply reconstruction, is a general term that describes the process of converting the basic signals recorded by the detector into collections of measurements associated to physical particles produced in the detector. The reconstruction is performed by algorithms, implemented in standardized computer software, shared across the experiment. The output of a reconstruction algorithm is a collection of derived measurements corresponding to the properties of a given particle. There are several layers of reconstruction, such that the output of one reconstruction algorithm is often used as an input to another reconstruction algorithm. The ultimate purpose of reconstruction is to produce collection of objects associated to physical particles that can be used in a physics analyses.

The first level of particle reconstruction described here consists of “Track” and “Cluster” reconstruction. Reconstructed tracks and clusters are the basic inputs to the higher-level particle reconstruction algorithms. There are actually many levels of reconstruction prior to this stage. These lower
levels convert signals read off of the detector into measured positions or energies, input to track and cluster reconstruction. These lower levels are not described in this thesis. The reader is directed to References [1, 2, 3] for more information.

Track reconstruction identifies the trajectories of charged particles. These trajectories are referred to as “Tracks”; track reconstruction is also referred to as “Track Finding”. A reconstructed track indicates the presence of a charged particle. In addition, the origin, direction, and momentum of a charged particle can be determined from its reconstructed track. Track finding is performed in both the Inner Detector (ID) and the Muon Spectrometer (MS). Charged particles traversing these detectors deposit energy, along their path, in the various detector sensors. The collection of sensor measurements, or “hits”, from a single charged particle follows the path of the particle through space. Track reconstruction associates hits to individual particles, and measures the trajectory from a three-dimensional fit to the position of the hits. Reconstructed tracks are critical for many aspects of particle reconstruction and identification. Details of how track reconstruction is performed in ATLAS can be found in References [1, 3].

Calorimeter clusters are the other basic input to particle reconstruction. Cluster reconstruction groups energies measured in the individual calorimeters cells into clusters of energy associated to incident particles. Electro-magnetic or hadronic particles traversing the calorimeter will interact with the detector material and produce a cascade of additional electro-magnetic or hadronic particles, which in turn interact and produce more particles. Occasionally, particles produced in this cascade will interact with the active material in the calorimeters, producing a signal in the calorimeter cells. Interacting particles incident to the calorimeter thus produce showers of particles whose energy is measured over many different calorimeter cells. Cluster reconstruction associates groups of neighboring cells to individual incident particles, and provides a measurement of the initial particle’s energy. Electro-magnetic particles, e.g. electrons and photons, tend to produce dense narrow showers, predominately contained in the electro-magnetic (EM) calorimeter. Hadronically interacting particles, e.g. pions and kaons, will produce broad showers, which penetrate deeply into the hadronic calorimeter. Cluster reconstruction is performed in both the electro-magnetic and hadronic calorimeters. Based on the location and density of the cluster, the algorithms can determine if they are predominately electro-magnetic or hadronic. Details of how cluster reconstruction is performed in ATLAS can be found in Reference [2].

The remainder of this section describes the higher-level reconstruction of particles produced in the detector. A schematic of the different particle signatures is shown in Figure 4.1. The figure shows a cut-away of the various sub-detectors in ATLAS and the characteristics of the types of particles
Figure 4.1: Schematic cut-away of the ATLAS detector. The different signatures of particles traversing the detector are shown.

which traverse the detector. Each of these are described in turn below.

One of the most important types of reconstructed particles are charged leptons. Charged leptons are the signature of electro-weak processes in hadron colliders. They provide clear signals which can be accurately and efficiently reconstructed. Throughout this thesis, charged leptons usually only refers to electrons and muons.

Muons are one of the simplest particles to identify. As indicated in Figure 4.1, muons traverse the entire ATLAS detector. They are reconstructed as tracks in the ID matched to tracks in the MS. Muons leave little energy in the electro-magnetic and hadronic calorimeters. Because all of the other interacting particles are stopped before reaching the MS, muons are identified simply by the fact that they made it to the MS. Muons produced from the decays of W and Z bosons tend to
have relatively large momentum, above 15 GeV, and be produced in isolation, with little surrounding
detector activity. When identifying these types of muons, a requirement is often made that the
energy of the reconstructed tracks and clusters near the reconstructed muon not exceed a certain
value. This is referred to as an isolation requirement and is effective at suppressing muons produced
from background processes such as meson decay in flight and heavy-flavor decay. As described in
Chapter 8, reconstructed muons are critical for the analyses presented in this thesis.

Electrons are the other type of cleanly reconstructed charged leptons. The signature of an electron
is shown in Figure 4.1. Electrons leave a track in the ID, and initiate an electro-magnetic shower in
the EM calorimeter; almost all of the energy is absorbed before reaching the hadronic calorimeter.
Electrons are reconstructed by matching reconstructed EM clusters to tracks reconstructed in the
ID. This signature suffers from large backgrounds from other types of charged particles. The ATLAS
detector provides an effective means of reducing these backgrounds. Like muons, electrons produced
from the decays of $W$ and $Z$ bosons are often selected using an isolation criteria. Reconstructed
electrons are central to the work presented in this thesis. Chapter 7 presents electron reconstruction
and identification in detail.

Taus are also charged leptons. However, from an experimental point, they are very different
from electrons and muons. Taus are not depicted in Figure 4.1 because they decay into other types of
particles before entering the detector. Around 40% of the time, taus decay to electrons or muons plus
neutrinos. These decays are indistinguishable from the electron and muon signatures described above.
The remainder of the time, taus decay to hadrons. The experimental signatures of these decays are
multiple hadronic showers matched to tracks in the ID. This signature suffers from large backgrounds
from other types of particles, which cannot readily be suppressed by experimental techniques. As a
result, in the remainder of this thesis only the leptonic tau decays are used to identify the presence
of a tau lepton.

Neutrinos are also members of the lepton family. However they only interact via the weak force,
and are thus not directly detected by ATLAS. They are depicted in Figure 4.1 as passing directly
through all of the sub-detectors. Although not directly observed, the presence of one or more neutrinos
can be inferred from an overall transverse momentum imbalance. This also provides a measurement
of the neutrino transverse momentum. As the reconstruction of neutrinos relies on global properties
of the entire event, the discussion of neutrino reconstruction is postponed until later in this section.

Photons are another type of particle that can be efficiently reconstructed and identified in ATLAS.
As with leptons, photons of interest are often produced in isolation. There are two experimental
signatures of photons, depending on if the photon underwent a conversion in the detector material
before entering the calorimeter. Photons which do not undergo such a conversion are referred to as unconverted. The signature of an un-converted photon is shown in Figure 4.1. Photons are neutral and thus leave no track in the ID. They produce an electro-magnetic shower upon entering the calorimeter. Un-converted photons are reconstructed as EM clusters which have no associated reconstructed track. Photons which undergo a conversion in the detector material are referred to as converted photons. A photon conversion produces two oppositely-charged electrons whose tracks form a vertex displaced from the interaction point. Dedicated reconstruction algorithms identify photon conversions from pairs of reconstructed tracks. Details of how photon reconstruction is performed in ATLAS can be found in Reference [4]. For the analyses presented in this thesis, reconstructed photons are primarily used to suppress electron background from converted photons.

Jet reconstruction is another critical ingredient for physics analyses. High energy colored particles, quarks and gluons, undergo a process referred to as hadronisation, whereby they convert into sprays of colorless culminated hadrons which emerge from the interaction point. The collection of these culminated particles is referred to as a jet. The measured energy and direction of a jet provides information about the initial quarks or gluons which participate in the physics processes of interest. Jet reconstruction groups reconstructed clusters and tracks into larger collections using various clustering algorithms. These algorithms are described in detail in Reference [5, 6]. The reconstruction of a high $p_T$ jet indicates the presence of a final state quark or gluon. The observed jet energy can also be used to infer the energy of the initiating parton. This is a particularly challenging aspect of jet reconstruction. This is referred to as the determination of the “Jet Energy Scale” and the “Jet Energy Resolution” [7]. The uncertainties associated with the jet energy scale and resolution are often the largest source of experimental uncertainty. In the analyses presented in this thesis, reconstructed jets are primarily used to veto the presence of final state quarks and gluons.

In general, the jet reconstruction algorithms cannot determine the type of parton that initiated a given jet. The exception are jets initiated by b-quarks. Bottom-quark flavored hadrons are relatively long-lived; they decay primarily via CKM-suppressed weak interactions. Jets associated to b-quarks thus contain relatively long-lived particles with typical decay lengths of order millimeter. A millimeter displacement from the interaction region is large enough to be resolved by the ID. Jets initiated by b-quarks, “b-jets”, can be identified from the reconstructed tracks associated to the jet. The process, referred to as “b-tagging”, identifies jets as b-jets if they have several tracks consistent with originating from a displaced vertex. Details on “b-tagging” in ATLAS can be found in Reference [8]. Reconstructed b-jets are used in the analyses presented in this thesis to identify processes involving top quarks, which are a significant source of background.
As discussed above, neutrinos can be detected from an overall transverse momentum imbalance. The overall transverse momentum imbalance is referred to as the “missing transverse energy” or $E_{T}^{\text{miss}}$. There are several ways the $E_{T}^{\text{miss}}$ can be determined. The most basic form of $E_{T}^{\text{miss}}$ is calculated by summing the $p_{T}$ of all the reconstructed calorimeter clusters and the $p_{T}$ of any reconstructed muons. Apart from neutrinos, all particles produced in a given interaction will deposit their energy in the calorimeters, or will be measured by the MS. Because the initial transverse momentum is known to be zero, any observed imbalance must be due to the presence of non-interacting particles: i.e. neutrinos. When summing over many clusters, the intrinsic resolution, and the non-Gaussian tails, of the detector response lead to a substantial uncertainty on the reconstructed $E_{T}^{\text{miss}}$. A more precise estimate of $E_{T}^{\text{miss}}$ can be obtained by summing the transverse momenta of higher-level objects. The energy measurements associated to identified leptons, photons, and jets are improved by dedicated calibrations specific to each identified particle type. By using these refined estimates of the particles transverse momenta, a better measurement of the missing energy can be made. As will be highlighted in Chapter 8, the detection of neutrinos through missing energy is critical to the analyses presented in this thesis.

An issue associated to particle reconstruction that often arises is duplicate objects. Different reconstruction algorithms may interpret input tracks and clusters in different ways. For example, the electro-magnetic shower produced by an electron, may be reconstructed as an electron, a jet, and a photon. In reality, these reconstructed objects are different interpretations of the same thing. In physics analyses, a decision must be made on the proper interpretation of the measured energy. This processes is referred to as “overlap removal”, and is done on a case-by-case basis depending on the physics analysis.

Figure 4.2 shows a visualization of a reconstructed event, illustrating many of the reconstructed objects discussed above. The transverse plane is shown in the upper left panel. Reconstructed tracks emerging from the collision are depicted as solid colored lines. Reconstructed clusters in the calorimeters are depicted as red and green bars, the height of which indicates the measured energy. The yellow blocks represent cell energies. The green bars correspond to EM clusters; the red bars correspond to hadronic clusters. The track shown in red, passes through the calorimeters to the MS, and corresponds to a reconstructed muon. The track shown in green matches a narrow EM cluster, and corresponds to a reconstructed electron. Two jets have been reconstructed. One of the reconstructed jets has tracks shown in blue associated to it; the other jet has yellow tracks associated to it. The event also has a large momentum imbalance, the direction of which is indicated by the dashed blue line. The lower left panel shows the same event in the z-y plane. The two reconstructed jets have been
identified as b-jets. The upper right panel is a close up of the tracks emerging from the interaction point. The tracks associated to the jets have displaced vertices, indicated in orange. This event has the characteristics of a $t\bar{t}$ event which decays di-leptonically into an electron, a muon, neutrinos, and two b-jets. As discussed in Chapter 8, di-lepton top events are a substantial background to the analyses performed in this thesis.

A yet higher-level of reconstruction exists in which identified particles are combined to reconstruct short-lived particles that do not directly interact with the detector. For example, two reconstructed electrons can be used to reconstruct a $Z$-boson. $Z$-bosons decay before leaving the interaction region, but can nevertheless be reconstructed by measuring their decay products. Various quantities associated to the $Z$-boson, e.g. its mass or momentum, can be measured despite not directly observing it. In fact, particles reconstructed in this way can even be used as inputs to yet another level of reconstruction in which their kinematics are combined to infer the properties of a parent particle. This is done in the case of the Higgs searches presented in this thesis. In the $H \rightarrow ZZ^{(*)} \rightarrow llll$ and $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ analyses, only the final products of the cascade are directly observed. These are used to infer the intermediate vector bosons, which are then used to reconstruct Higgs candidates.

4.2 Trigger

The trigger is a critical aspect of doing physics at a hadron collider. Many of the most interesting physics processes have very small cross sections. Large numbers of collisions are needed to produce significant quantities of these rare events. In order to produce these large numbers of collisions, the LHC operates at a high rate. Beam crossings, with many collisions per crossing, occur at a rate of 40 million per second. This high event rate poses a serious problem, as ATLAS can only afford to save around 400 events per second. The trigger system performs real-time event selection to reduce the number of recorded events to 400 per second. This amounts to saving one event for every 100,000 produced by the LHC. The trigger is optimized to select events in a way such that the interesting, rare events are not part of the 100,000.

The ATLAS trigger is composed of three levels: L1, L2, and the Event Filter (EF). The first level analyzes all 40 million events per second and selects 1 in $\sim 500$ events to proceed to the next level. The L1 event selection is based on basic calorimeter clustering and track finding in the MS. The L1 trigger selects events with high $p_T$ muons, or clusters consistent with high $p_T$ objects. Because the L1 decisions need to be made extremely quickly, in 2.5 microseconds, the L1 reconstruction algorithms are implemented directly in hardware. The L1 selection reduces the event rate from 40 million per second to 75 thousand per second.
Figure 4.2: Event display of a $t\bar{t}$ di-lepton candidate in the $e\mu$-channel with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the $E_T^{miss}$ direction is indicated by the blue dotted line in the x-y view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses in the upper right.
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The L2 and EF stages of the trigger are performed using computer farms. L2 selects 1 in 15 events to proceed to the EF, reducing the event rate to 5 thousand per second. Event selection at L2 refines the reconstruction of objects selected at L1. Fast, 50 milliseconds per event, algorithms reconstruct leptons, photons, and jets around the objects found in L1. The L2 decisions are based on these reconstructed objects.

The EF selects 1 in 10 events to be written to tape for use in physics analyses. This reduces the total event rate to 400 per second. The EF decisions are made using algorithms similar to those used to reconstruct objects in physics analyses.

The analyses presented in this thesis use events triggered by reconstructed electrons and muons. High $p_T$ leptons, above around 20 GeV, can be efficiently identified and have relatively low levels of background. These leptons provide an effective way of selecting events in the trigger. Over half of the 400 events per second are selected on the basis of having a high $p_T$ electron or muon. The generic selection of a single identified lepton supports a broad range of physics analyses. The details of the electron selection used in the trigger are described in Chapter 7. More information on the ATLAS trigger system can be found in Reference [9, 10].

4.3 Pile-Up

Overlapping signals from different $pp$ collisions are a particularly challenging complication for reconstruction at the LHC. This phenomena is referred to as “Event Pile-up” or simply “Pile-up”. There are two types of pile-up: in-time pile-up and out-of-time pile-up.

In-time pile-up occurs when multiple $pp$ collisions take place in the detector simultaneously, during the same bunch crossing. The high luminosity LHC operating conditions give rise to many $pp$ interactions per bunch crossing. Figure 4.3 shows the average number of interactions per crossing for the data used in the analyses presented in this thesis. Typical events in the $\sqrt{s} = 7$ TeV 2011 data set have 10 overlapping interactions; in the $\sqrt{s} = 8$ TeV 2012 data set, a typical event has around 20 overlapping interactions. The particles produced in these additional pile-up events obscure the reconstruction of the primary event of interest. The additional energy deposited in the detector as a result of pile-up will effect the measured energies in the calorimeter. This has a large effect on lepton isolation energies and the measurement of jet energies. As will be presented in Chapter 7, in-time pile-up also has a significant impact on the identification of electrons. In time pile-up significantly degrades the measurement of missing energy. As discussed in Chapter 11 this has direct consequences for physics analyses.

Out-of-time pile-up is more benign. It occurs when signals from events in previous bunch cross-
Figure 4.3: Mean number of interactions per bunch crossing for 2011 and 2012 data. The plot shows the full 2011 run and 2012 data taken between April and June.

ings interfere with the current bunch crossing. Out-of-time pile-up is primarily an issue in the EM calorimeter. Because of its long readout time, energy deposits from previous bunch crossings can affect the measured energy of EM clusters in the current crossing. Interestingly, out-of-time pile-up leads to negative energy contributions to clusters in the current event [11]. Although out-of-time pile-up can degrade energy resolution, but is typically less of a problem than in-time pile-up.

4.4 Commissioning

Commissioning is a generic term that refers to the process of making the reconstruction algorithms work as they are intended, and to understanding how what is reconstructed in the detector corresponds to what actually happened in the detector. Commissioning is one of the most important and challenging aspects of making an experiment such as ATLAS work. It effects all physics analyses. A significant portion of this thesis is devoted to commissioning activities.

Roughly speaking, commissioning is separated into two spheres: detector commissioning, and the commissioning of the reconstructed objects. Detector commissioning involves understanding the real-world operating conditions of the detector and calibrating the lower-level reconstruction inputs. Converting voltages and times recorded by detector electronics into measured positions and energies is complicated. This process often relies on conditions which change with time, or on detector specific parameters that must be precisely determined. One example is the detector alignment. Accurately
determining the position of a measurement within ATLAS requires a precise knowledge of the positions of the individual detector elements making the measurements. Determining the in situ detector alignment is necessary for understanding the inputs to track finding, which as discussed above, is essential for all other reconstruction levels. Chapters 5 and 6, discuss detector alignment in detail.

Commissioning the reconstructed objects involves making the various reconstruction algorithms work properly and understanding their outputs. This involves: determining the energy scale and resolution of reconstructed objects, tuning and measuring the efficiencies of various particle identification algorithms, and defining the event selection used in the trigger. These commissioning steps are critical for understanding reconstructed objects at a level that can be used in physics analyses. Chapter 7 describes the optimization of the electron identification algorithms and the various electron selections used in the trigger.

As mentioned above, leptons are crucial for doing physics at hadron colliders. In addition, the standard model provides clean sources of leptons which can serve as standard candles that can be used in commissioning. An example are Z bosons. Z bosons are an abundant, well-known source of leptons. They are used throughout this thesis in what is known as the “Tag-and-Probe” method. Requiring one fully identified lepton and a second basic object, e.g. a reconstructed track or cluster, which form an invariant mass consistent with the known Z boson mass, gives a clean sample of unbiased leptons. This unbiased sample of leptons can then be used to commission the various levels of reconstruction. For example, the lepton identification efficiency can be optimized or measured, using this sample. The tag-and-probe technique has been used throughout this thesis.

4.5 Conclusion

This chapter has provided a basic introduction to the particle reconstruction used throughout this thesis. The reconstructed particles are inputs to all physics analyses in ATLAS. They are the bridge from signals recorded in the detector, to four-vectors of final state particles. Understanding these reconstructed objects is a prerequisite for all measurements, searches, or discoveries.

The following three chapters are focused on understanding various aspects of the reconstruction, building on ideas introduced here. Chapters 5 and 6 are focused on detector alignment, crucial for understanding track reconstruction, one of the basic inputs to particle identification. Chapter 7 describes the reconstruction and identification of electrons, which are critical to the analyses presented in the remainder of this thesis.
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4.6 Bibliography


