Characteristics of the ATLAS and CMS detectors

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The goal for the detection of new physics processes in particle collisions at Large Hadron Collider energies, combined with the broad spectrum of possibilities for how the physics might be manifest, leads to detectors of unprecedented scope and size for particle physics experiments at colliders. The resulting two detectors, ATLAS (A Toroidal LHC ApparatuS) and CMS (compact muon spectrometer), must search for the new physics processes within very complex events arising from the very high-energy collisions. The two experiments share many basic design features—in particular, the need for very selective triggering to weed out the bulk of the uninteresting events; the order in which detector types are arrayed in order to provide maximum information about each event; and the very large angular coverage required to constrain the energy carried by any non-interacting particles. However, within these basic constraints, the detectors are quite different given the different emphases placed on issues such as resolution and background rejection. Both common features and the distinct differences will be presented.

Keywords: Large Hadron Collider; particle detectors; high-energy physics

1. Introduction

The CERN Large Hadron Collider (LHC) accelerates and then collides protons at very high energies. Presently, the centre-of-mass energy is 7 TeV, and this will increase to 14 TeV a few years from now. In addition, the frequency and total number of collisions per second is very large in order to provide a sufficient quantity of data to search for rare processes. To study the complex events resulting from the collisions, two general purpose detectors, ATLAS (A Toroidal LHC ApparatuS) [1] and CMS (compact muon spectrometer) [2], have been built, installed at the LHC, commissioned and are now collecting data. The data collected to date have already yielded a number of physics papers, and the design choices made by each experiment have been validated.

Given the high energy of the collisions, the LHC copiously produces the particles that are thought to have populated the very early Universe before nuclei or atoms formed. It is anticipated that this will most probably include particles not discovered in previous physics searches using either earlier lower energy accelerators or the interactions of cosmic rays from space, owing to the difficulty

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One contribution of 15 to a Discussion Meeting Issue ‘Physics at the high-energy frontier: the Large Hadron Collider project’.
in seeing the details of events produced by cosmic ray showers. The discovery of this ‘new physics’ is the primary purpose for building the LHC. Figure 1 shows the known set of elementary particles, which provide our present understanding of matter and the forces by which they interact (excluding gravity) going back to the early Universe. These constitute what is called the Standard Model of particle physics. Combinations of these particles, bound by the force carriers, make up protons and neutrons (composed of the first-generation quarks), nuclei (composed of protons and neutrons) and atoms (composed of nuclei and electrons). The force carriers are responsible for the strong interactions producing protons, neutrons and nuclei (owing to gluons, indicated as $g$), the electromagnetic interactions producing atoms (owing to photons, indicated as $\gamma$) and the weak interactions are responsible for radioactive decay of unstable nuclei (owing to the $Z$ and $W$). Leptons and quarks in a given row have the same interactions (for example, the same electric charge) but different masses. The second- and third-generation particles are heavier than those of the first generation and spontaneously decay through the weak interactions to the lighter particles after direct production at accelerators. The neutrinos have only weak interactions and therefore easily penetrate large quantities of material without directly interacting.

Of these elementary particles produced at the LHC, the quarks are not directly observable as they are always confined inside ‘hadrons’ (protons, neutrons, mesons and hyperons), which are the particles that can be directly detected in an experimental apparatus. So, it is the task of the experiments to record these hadrons as well as leptons and photons, which can be directly observed in principle. Neutrinos cannot be directly detected, but their production can be inferred through the energy and momentum missing in the event after all the visible energy and momentum are added together for the detectable particles. Finally, a characteristic of the strong interactions is the production of jets of hadrons. A jet is a collection of hadrons travelling in approximately the same
direction. These result from high-energy elementary quarks or gluons that have ‘hadronized’. Thus, we typically do not find isolated hadrons, but rather a jet of hadrons as the signature of quark production.

It is expected that particles resulting from new physics will yield in the detector, through spontaneous decay, some number of the Standard Model particles shown in figure 1 or be non-interacting, like neutrinos, if they do not have strong or electromagnetic interactions. The particles from the new physics are typically searched for in the data by combining the direct measurements of energy and momentum for the hadrons, leptons and photons, and inferring the existence of a parent for these particles. The mass scale we are interested in, typically larger than about 100 GeV, makes it possible to see signals above background in the data for many examples of new physics processes that have been explored by the theoretical community. We need to deduce the physics framework and mass, charge and spin of such new particles from the decay patterns and rate of production seen in the data. This provides the motivation for the broad detection capabilities of ATLAS and CMS, which need to detect jets, decay vertices for particles that decay owing to the weak interactions at locations displaced from the beam interaction region, photons (the only force carrier directly visible) and the various kinds of leptons. In addition, through the addition of all visible energy carried by detected particles, a measure of the invisible energy can be deduced. In practice this is only possible transverse to the beam directions since the remnants of the collision that do not exit the beam pipe can carry away unmeasured longitudinal momentum. This leads to the concept of transverse energy measurement, which is the energy measured in the detector treated as a vector. It is therefore approximately the transverse momentum. Large values of missing transverse energy can distinguish the production of new non-interacting heavy particles from neutrinos produced in weak decays, which typically have transverse energy values well below 100 GeV.

The Standard Model, as presently understood, fails to account for two phenomena visible in large-scale astronomical measurements and also requires an additional component, called the Higgs field, for mathematical consistency of the weak interactions. The two phenomena revealed through astronomical measurements go under the name of dark matter and dark energy. Dark matter is most probably made of particles, which have been critical to the formation of galaxies through gravitational interactions, and now dominate the mass in the Universe. The search for these at the LHC is an important part of the physics programme and strongly motivates the need to measure missing transverse energy because these particles do not have strong or electromagnetic interactions. Dark energy is a form of energy that affects the geometry of space and time and seems unrelated to any particle type. So far, it can only be studied with telescopes; so the LHC will probably not have a direct impact on this topic. The Higgs field uniformly permeates space and provides the particles in figure 1 with their mass. The consistency condition for the weak interactions requires that we find further evidence for this within the LHC energy window. The simplest example would be an accompanying single particle called the Higgs boson. The decay pattern of this particle depends on its mass, which provides a crucial specification for the ATLAS and CMS detectors, which is that they must be able to discover the Higgs boson over the full range of possible masses. This requires very broad detection capabilities.
2. General detector characteristics

The ATLAS and CMS detectors are composed of arrays of particle detection elements. At the most basic level, such an element measures the local deposition of ionization in a medium. The ionization is collected on electrodes because of an electric field in the medium, resulting in an electrical signal that can be read out into a data stream. The ionization may be the result of the traversal of the medium by a single charged particle, or the traversal of showers of particles resulting from interaction of the particle we wish to detect. The detection elements are arrayed to allow us to discern a pattern of energy deposits, which we attribute to the particles produced in the collision. The signals and detectors are organized so we can measure the energy and momentum of the various particles either by a reconstructed trajectory in a magnetic field for charged particles or through the proportionality of the signal to the energy deposited for particle showers (after typically a number of corrections that are based on models of the detector properties and calibration data). Different particles that traverse the detector are distinguished by the type of interactions they have with the medium: strong, electromagnetic or weak. For the weak interactions, the particle itself is undetectable, unless it decays spontaneously within the detector volume. Common to both ATLAS and CMS, the detector is organized as concentric shells with end caps, where each shell has a specific detection task. The general scheme is shown in figure 2, which shows a transverse view of a detector, and is based on ATLAS.

The innermost layers (called the inner tracker) are immersed in a solenoidal magnetic field and provide track trajectory measurement for the charged particles.
Typically, the highest precision in position measurement is provided by elements near the origin where we wish to see displaced decay vertices. It is desirable to minimize the overall mass of the inner tracker to avoid creating unwanted detector hits from particles created through interactions in the material of the tracker itself. Sitting closest to the interaction point from which the particles emanate, the inner tracker has to be fine-grained to see the individual hits in a dense environment of many hits.

Following the inner tracker are calorimeters, which provide information by interactions of the incident particles in dense materials. The calorimeters must fully absorb the particle energies from the interactions to avoid generating spurious missing transverse energy by incomplete measurement. The requirement for total absorption defines the transverse dimensions of these large and expensive parts of the detector.

The first calorimeter sections (electromagnetic calorimeter) measure the energy and hit location of photons and electrons based on the creation of electromagnetic showers. Such showers consist of the many electron–positron pairs that are created when a high-energy photon or electron interacts in a dense medium. Choosing a calorimeter material with a small radiation length, which is the length over which an incident electron has radiated about 63 per cent of its energy, results in narrow well-contained showers, allowing good shower position measurement and good assignment of the energy to the individual incident particles in the event. Electrons are discriminated from photons by also having a visible trajectory in the inner tracker. The radiator material in the electromagnetic calorimeter typically is chosen to have a radiation length of between 5 mm and 1 cm and the total number of radiation lengths to absorb the electromagnetic shower is about 25 radiation lengths.

The outer calorimeter sections (hadronic calorimeter) absorb energy from interactions of the bulk of the hadrons and require much more material. The material is characterized by an interaction length, which is the length needed for about 63 per cent of the hadrons to interact strongly. The total number of interaction lengths needed is about 10, with the electromagnetic calorimeters providing approximately the first interaction length. The hadronic showers stemming from strong interactions in the calorimeter material are typically much broader than electromagnetic showers, and the associated energy measurement is much less precise. Contributing to the uncertainties are fluctuations in the amount of electromagnetic energy produced in the hadron cascade from decays of the $\pi^0$ component (which decays immediately into two photons) of the shower, because the calorimeters respond differently to photons and long-lived hadrons. An interaction length for the material chosen for the hadron calorimeters is typically about 15 cm.

The final, outermost, element in the detectors (muon detection system) identifies muons as charged particles seen in the inner tracker that then penetrate the material of the calorimeters without showering. The muon detection system requires layers of detection devices that measure the momentum through magnetic bending, which can then be compared with the inner tracker measurement for validation. As the outermost element, the muon system is very large, although the individual measuring devices do not need high granularity because the density of hits is much lower than in the inner tracker.
Figure 3. A two-jet event as seen in the ATLAS detector. (Online version in colour.)

Figure 3, which shows an LHC event in the ATLAS detector, illustrates several additional features that are common to both experiments:

— There is a great deal of detailed and complicated information collected in the inner tracker.

— The detector is very long along the beam directions mirroring the spread in particle trajectories (i.e. the complexity of the event) but also to minimize the transverse energy that can escape detection by going down the beam pipes. The very hermetic detectors have a beam hole of about 1° in each direction.

— The calorimeter information, presented on the right in the figure, where the detector has been unrolled, provides a simplified but clear view of the event characteristics. This is a two-jet event. The clarity and simplicity of the calorimeter information is used to provide a major component of the event trigger, a critical component of these experiments. The trigger provides the decision, based on the information available from the various detector elements, as to whether the event is likely to be of interest and therefore should be recorded. This requires very fast decision-making.

— The detector calorimeters will be able to distinctly detect and measure each of the jet’s properties separately for events with many jets in the final state, given the small fraction of the calorimeter taken up by each jet.

— The outer muon system, shown in the top left of the figure only, has very few hits, as expected for fully absorbing calorimeters.

Despite a common detector strategy, the two experiments are not identical because of the many trade-offs that are required to reach a final detailed detector design. Some examples are the:

— choice of granularity of detection elements;
— number of measurement layers;
— outer radius of the inner tracking detector;
— strength and shape of the magnetic field;
— choice of detection medium for the calorimetry;
— different technologies for both detector elements and readout;
— precision goal for the different elements of the detector;
— strategies for background rejection;
— triggering strategies; and
— cost containment and optimization.

ATLAS and CMS have largely the same physics objectives; yet the final detectors are quite different as the balance between the earlier mentioned items has been chosen differently. The performance of both detectors, however, goes well beyond what has been achieved in previous experiments and a number of choices made by the experiments are completely new to the field.

3. Details of the ATLAS detector

The ATLAS detector is shown in figure 4. It is very large, measuring 48 m in length and 24 m in height. The outer dimensions are determined by three sets of toroidal magnets, which are preceded and followed by detectors. The toroids have no extra material, besides the coils and their supports, to minimize scattering. The resulting toroidal magnetic field surrounding the interaction point together with the tracking detectors gives a very precise measurement of the momentum of charged particles. Closer to the beam than the toroids are the calorimeters, whose functions have been described earlier. A thin coil providing a 2 T solenoidal magnetic field sits inside the calorimeters. Closest to the beam is the inner tracker.
Figure 5. The ATLAS inner tracker with inner silicon arrays and outer straw tubes. (Online version in colour.)

Besides the toroids, a number of devices in the detector are either novel or very large extrapolations of technologies used in previous experiments. Several of these are described below.

Figure 5 shows a drawing of the inner tracker, emphasizing the many forward and backward detector arrays. The silicon tracking devices, which cover from the outside of the beam tube to about 60 cm radius, are made of arrays of fully depleted patterned silicon diodes connected to readout electronics channels. Only the outermost array is shown for the central barrel. The geometry has been chosen to provide seven precision space-point measurements for most track trajectories, with measurement precision in the bend plane of about 10–20 \mu m. The inner three measurements, closest to the beam, are provided by highly segmented pixel detectors, which figure prominently in both ATLAS and CMS.

Covering a radial region between about 60 cm and 1 m are a large number of closely spaced straw tubes of 4 mm diameter. These are each filled with a gas and an amplification wire in the straw centre. The closely spaced straw tubes allow a nearly continuous measurement of track trajectories. Highly relativistic charged particles (primarily electrons) produce transition radiation photons in the material of the straw system. The conversion of these photons in the gas of the straws provides very large signals that accompany the trajectory of an electron, allowing an additional tool for electron identification.

Figure 6 shows the concept and some of the parts making up the ATLAS electromagnetic calorimeter. The showering material is lead and the shower is sampled in the liquid argon between the lead concertinaed plates. The ionization deposited in the liquid argon is collected on copper electrodes, also shown. The accordion structure allows very uniform sampling as well as the collection of signals along the length of the shower. The electrodes can be segmented in a manner chosen to allow good separation between neighbouring showers and also to give some information along the length of a shower.

Figure 7 shows the inner part of the detector assembly surrounded by the large barrel toroids used for the muon identification and momentum measurement.
Figure 6. Concept and some of the parts making up the ATLAS electromagnetic calorimeter. (Online version in colour.)

Figure 7. The ATLAS barrel toroid assembly. (Online version in colour.)
4. Details of the CMS detector

A cut-away drawing of the CMS detector is shown in figure 8. Except for the muon detection system, the other detection devices sit inside a very large coil creating a 4 T solenoidal magnetic field. The combination of field and size for the coil go well beyond what has been attempted in earlier particle physics experiments. The flux return for the field of the solenoid is channelled in large iron plates that are segmented to allow interspersed gas-filled ionization chambers to measure the bending of muons in the magnetic field in the iron. Several of the other novel systems in CMS are described below.

The inner tracker for CMS is entirely made of arrays of individual silicon wafers. Figure 9 shows what a barrel detection layer looks like. The number of layers is 13, going out in radius from just outside the beam tube to about 110 cm, and the precision in the bend plane measurement varies from about 10 μm on the inside, where the pixel layers are arrayed, to about 65 μm on the outside using strip layers. The total area of silicon is about 200 m², about three times the silicon area in ATLAS, which uses analogous detectors, but only out to about 60 cm.

The electromagnetic calorimeter in CMS is made of specially developed lead tungstate crystals. These crystals produce very fast signals and are transparent, although they are approximately as dense as lead. The crystals are each about 23 cm long and 2.2 × 2.2 cm at the front face. The detector has approximately 76 000 such crystals. Figure 10 shows some of the crystals as they are prepared to serve as shower detectors.

Figure 11 shows the CMS 4 T coil and parts of the flux return and muon detectors.
5. Some emphases and trade-offs made by the detector collaborations

The design choices for ATLAS and CMS provide special emphasis for aspects of the event reconstruction process. The different choices made should result in rather different systematic uncertainties in measurements, making the exploratory LHC physics programme more robust.
A special emphasis of CMS is excellent resolution for charged particles, photons and electrons. For charged particles this is a result of a large magnetic field (4 T) and large tracking radius (1.1 m) for the inner tracker. For photons and electrons, this is a result of using crystals for the calorimeter material. These choices result in a single-particle resolution a few times better than for ATLAS. Muon detection is provided by the measurements in the ionization chambers positioned within the iron magnetic flux return. Precision measurement of muon track parameters is provided by the inner tracker and at very high momentum by the inner tracker and outer muon system combined. This is a cost-effective way to carry out the muon measurement.

For ATLAS, a special emphasis is the excellent background rejection obtained through using more measurements than the minimum required to provide cross-checks, combined with good calorimeter resolution. For electrons, transition radiation in the straw tube tracker can be combined with the momentum and energy measurement in the tracker and calorimeter for identifying electrons and rejecting background. The electromagnetic calorimeter is very fine-grained in the transverse direction and provides four longitudinal measurements along each shower; the hadronic calorimeter has three longitudinal samples, to allow careful examination of showers. The muon track parameter measurement using the outer air-core toroids can be compared with the reasonably high-precision inner tracker measurement for excellent background rejection. The use of separate toroids in the forward and backward directions maintains the very high-precision muon measurement for forward going particles.
The hadron calorimeters for ATLAS and CMS also illustrate interesting design choices, which are constrained by the overall detector design. For both ATLAS and CMS, the detection medium for the hadron calorimeter is scintillator, which provides fast signals and has a moderate cost. The resolution depends on the sampling fraction and sampling frequency for the scintillator versus the inactive material. Larger values for the scintillator sampling fraction and sampling frequency provide better overall resolution of the shower energy.

For CMS, the hadron calorimeter is inside the magnetic field; so the radiator has to be non-magnetic. It also has to be as compact as possible since the very large coil radius is determined by the radius of the calorimeter. The resulting CMS choice of radiator is copper.

For ATLAS, the hadron calorimeter is outside the coil and can therefore be larger. The material chosen is iron for cost minimization. The resulting plate thicknesses for ATLAS and CMS are shown in Table 1, in units of both radiation length and interaction length.

Some approximate resolution numbers that result from the various design choices are listed in Table 2.

### Table 1. Plate thicknesses for ATLAS and CMS.

<table>
<thead>
<tr>
<th></th>
<th>thickness (radiation length)</th>
<th>thickness (interaction lengths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (Fe)</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>CMS (Cu)</td>
<td>3.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

### Table 2. Percentage measuring error for a 100 GeV particle or jet.

<table>
<thead>
<tr>
<th></th>
<th>ATLAS (%)</th>
<th>CMS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inner tracker (charged particle)</td>
<td>3.8</td>
<td>1</td>
</tr>
<tr>
<td>electromagnetic calorimeter (electron or photon)</td>
<td>1.1</td>
<td>0.5</td>
</tr>
<tr>
<td>hadronic calorimeter (jet of hadrons)</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>muon system (muon)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

#### 6. Event triggers

At the design luminosity for the LHC, ATLAS and CMS will see about 25 proton–proton interactions per bunch crossing, which occurs every 25 ns. From this flood of data, a small number of interesting events have to be selected for eventual examination off-line. This is the job of the event trigger, which works by examination of events using successively better and more complete information for each event. The first part of the trigger, which is organized in a hierarchical way, is called level 1. This involves specially constructed experiment-specific hardware, which has to collect and examine the information from the detector. This takes time and the full detector information has to be stored during this process. After the level 1 trigger has made a decision, the event information is either discarded (most of the time) or passed on for more stringent analysis. The successful passing
of the level 1 trigger results in the remainder of the event information being read out, including the inner tracker hits. These are not used in the level 1 trigger and have to be stored during the time it takes for the level 1 decision. The remainder of the trigger decision process can use commercial switches and computers for a more detailed analysis of each event. The use of commercial devices in as much of the trigger as possible allows each experiment to upgrade and profit over time from advances in industrial technology.

The level 1 trigger for both ATLAS and CMS uses the calorimeters to find large transverse energy electrons, photons or hadronic jets and also the muon system to find large transverse momentum muons. From these, the missing transverse energy can be calculated. After the level 1 trigger, inner detector information can also be used to improve the understanding of the event, including better selection of electrons and muons. Both ATLAS and CMS have flexible triggers, allowing trigger menus to be specified. These can evolve as the interaction rate increases or our knowledge of the physics at the LHC energy improves. A summary of the overall rate challenge is given as follows:

- interaction rate: 1 GHz;
- bunch-crossing rate: 40 MHz;
- level 1 output: 100 kHz (50 kHz initially);
- output to storage: 100 Hz was the design; with commercial improvements, a few hundred hertz;
- average event size: 1 MB; and
- data production: few TB per day.

7. Upgrades

The previous sections have discussed ATLAS and CMS as built. These detectors are expected to collect data at the LHC for many years. As a result, they need to evolve over time, with changes to the detector motivated by our better understanding of the physics probed at the LHC energy scale as well as advances in technology. In general, large structures (for example, magnets or calorimeter structures) are very difficult to replace and these are expected to last for the lifetime of the experiment. However, both computing capability and electronics evolve rapidly with time, allowing the possibility of upgrading the detectors by including new commercial developments. One example is the improvement of the inner tracker pixel detectors (either by the addition of more layers or by the replacement of existing layers), which are modest in area and can benefit significantly from the use of newer electronic technologies for their readout. Another major area in which we can expect to see upgrades is the trigger, because this is very much based on the latest electronics. Given its critical role in selecting the events that will eventually be examined, the experimental collaborations are strongly motivated to enhance the trigger capability.

One area not prominently included in the trigger is the complex inner tracker information. Both ATLAS and CMS are examining how to include such information at an earlier stage in the trigger and in a more complete way. The first example will probably be through the finding of most of the tracks and vertices in parallel, using associative memory chips and simplified track parameter fits. The possibility now exists to examine in parallel large numbers of hit patterns that
form specified curves in the set of inner tracker layers. For example, it is possible to examine $10^9$ patterns in parallel, allowing near simultaneous finding of all charged tracks above a selected transverse momentum in the inner tracker. This can only be done after a first level trigger when all the inner tracker information has been acquired from the detector. Under development on a longer time scale is the inclusion of inner tracking information within the first level trigger itself. This can only be done when the inner trackers are fully replaced, which is likely to be after a decade of data collection. Such an increased capability would be helpful in enhancing the muon trigger by earlier comparison of inner tracker trajectories with trajectories seen in the outer muon system.

8. Summary and conclusions

The LHC has initiated accelerator-based physics in a new energy regime where we anticipate finding physics that will explain some of the missing pieces in our otherwise very comprehensive picture of particles and their interactions. To study the physics with sufficient data requires very high interaction rates and the study of very complex events resulting from the collisions of the beams circulating in the LHC. Two large detectors, ATLAS and CMS, have been constructed to collect the data and provide the information to allow an understanding of the events produced. Many of the individual detection elements employed by the two experiments are either novel or very large extrapolations of technologies used in previous experiments. These elements are based on several years of research and development followed by several years of construction. The two experiments are now collecting data, and the design choices and predicted performance have been validated. The search for new physics is underway.

References
