Chapter 2
The Experiment

The heaviest particle of the Standard Model is the top quark at 173 GeV, followed by the H (125 GeV), Z (91.2 GeV), and W (80.4 GeV) bosons. To produce these particles, you need to give the system at least enough energy to cover the mass. In addition, for a given targeted process, only a small fraction of collisions will actually produce that process, so a large number of collisions, high *luminosity*, is needed to accumulate enough events to draw interesting conclusions. Finally, you need a detector capable of measuring the type, energy, and momentum of the particles produced.

Astrophysical events often involve enormous amounts of energy, and the most energetic particles detected have come from space. However, this kind of data is not useful for directly measuring properties of the Higgs boson, which requires detecting multiple decay products.

The Large Hadron Collider (LHC) is designed to cover the first two requirements, energy and luminosity. The collisions of the LHC are at the highest energy and luminosity of any collider to date. The Compact Muon Solenoid (CMS) experiment is designed to measure particle decays to high precision. Although they were also designed to be capable of many different analyses, one of the primary design goals of the LHC and its detectors was to produce, discover, and characterize the Higgs boson.

2.1 The Large Hadron Collider

The Large Hadron Collider is located 100 m under the French and Swiss countryside near Geneva, shown in Fig. 2.1. It accelerates protons around a 27 km tunnel and collides them together. Several smaller accelerators are used to accelerate the protons to successively higher energies until they are injected from the Super Proton Synchrotron (SPS, shown in blue in the picture) into the LHC at an energy of

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Fig. 2.1 An aerial picture of the ground above the LHC, with its path shown in a circle and the interaction points labeled with the experiments located there. This picture is from [1]

450 GeV. All around the tunnel, a series of 1232 dipole magnets direct the protons through the curves of the tunnel, and higher order magnets focus the beams. The protons circulate in two beams, traveling in opposite directions. Once they are accelerated to the final energy, currently 6.5 TeV, the beams are brought together to collide at four interaction points, with a center of mass energy of 13 TeV.

Each interaction point houses one of the four large LHC experiments: ATLAS, CMS, LHCb, and ALICE. ATLAS and CMS are both general-purpose detectors, designed to be sensitive to multiple types of possible new physics. LHCb is optimized for measurements in quark flavor physics, particularly for precise measurements of hadrons containing the *b* quark. ALICE is designed for the periods of time when the LHC collides ion nuclei together and particularly focuses on studying the quark–gluon plasma that can be formed at the extremely high temperatures generated by the collisions.

During a fill, the LHC collides bunches of protons every 25 ns. Approximately 2800 bunches at a time circulate in the tunnel, and each one contains around 10^{11} protons. Each bunch crossing results in an average of 37–38 collisions, giving a total of 1.5 billion collisions per second. Most of those collisions do not produce anything interesting. In order to calculate the expected number of collisions that result in a particular process, we use the process' *cross section*, measured in units

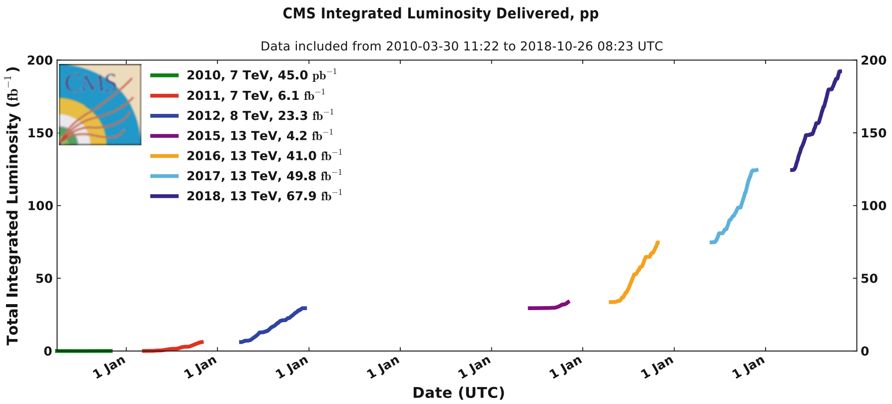

Fig. 2.2 Plots of the integrated luminosity delivered to CMS over the years since the start of LHC operations. This plot is from [2]

of area, and the integrated luminosity, with dimensions of $\frac{1}{\text{area}}$. The cross section is the quantum mechanical equivalent of the cross sectional area of a bucket, and the integrated luminosity is the equivalent of the number of raindrops falling per area. The product of the two gives the number of raindrops that fell into the bucket.

Due to improvements in the LHC over the years, the luminosity delivered has increased, as shown in Fig. 2.2. Additionally, cross sections for processes generally increase at larger energy, giving a further boost to the number of events involving rare processes in the more recent runs of the LHC.

2.2 The CMS Experiment

The Compact Muon Solenoid detector is one of the multi-purpose detectors at the LHC. It is built to cover as much angular space as possible, so that it can detect almost all of the particles produced in collisions. It is named for three defining features of its construction:

- CMS is compact: although it is only a fifth the volume of ATLAS, it weighs almost twice as much.
- CMS is especially optimized for precise measurements of muons, as the next few sections will discuss.
- The 3.8 T solenoid magnet is especially strong in order to increase the precision of momentum measurements of long-lived charged particles.

The detector is arranged in layers, each sensitive to different types of particles. The innermost layer, the tracker, measures the trajectory of all charged particles while having as little effect as possible on their momentum and energy. The electromagnetic calorimeter, or ECAL, measures the energy of electrons and photons,

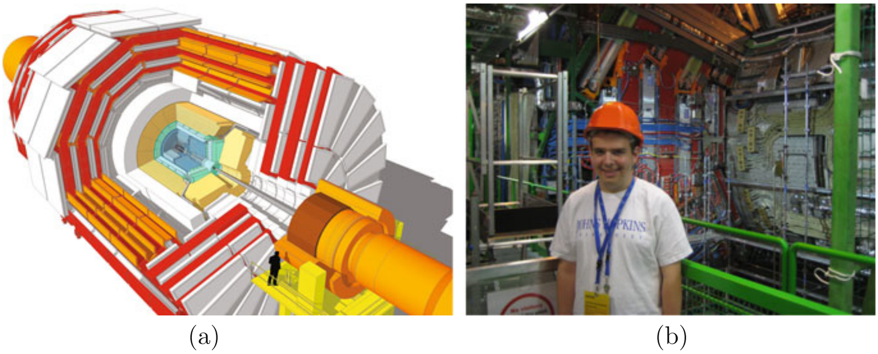

Fig. 2.3 (**a**) A cut open view of the CMS detector [3]. (**b**) A picture of me standing in front of the CMS detector, taken in the summer of 2013 [4]. The most distinctive parts visible are the interleaved white muon chambers and red return yoke

absorbing them in the process, while having a small effect on hadronic particles and muons. The hadronic calorimeter absorbs hadronic particles and measures *their* energy, while muons are again mostly unaffected. Finally, the muon system provides a second measurement of muons' momentum, and matching to tracks in the tracker identifies those tracks as belonging to muons.

Figure 2.3 shows a cross section of the CMS detector and a picture of me standing in front of it.

2.2.1 Coordinate System

The natural geometry for a collider experiment's detector is cylindrical. There is one preferred axis, the z axis where the protons enter the detector, but the x and y axes are, for the purpose of the collisions, arbitrary. The various parts of the detector are built in two parts: a barrel, to measure particles that travel perpendicular to the beam axis, and an endcap, to measure particles that travel at larger angles. Although the barrel and endcap are of a given subdetector provide the same types of measurements, they are constructed somewhat differently. The endcaps receive a higher flux of particles, which adds two additional constraints to their design: they need to withstand more intense conditions, and they must perform higher granularity measurements in order to distinguish between particles that come at the same time.

The z axis is chosen to be along the beamline. The y axis points up towards the sky, and the x axis is horizontal. Although collisions are azimuthally symmetric, gravity points in the $-y$ direction, which is important when considering the construction of the detector and its movement over time. In addition, cosmic rays, which are used in calibration, typically travel in an almost vertical direction.

We often use the standard azimuthal angle ϕ. While the radial angle θ is used occasionally, particularly when cosmic rays are involved, the more useful quantity for particle collisions is the pseudorapidity:

$$\eta = -\ln \tan \frac{\theta}{2} \tag{2.1}$$

Pseudorapidity transforms more nicely than θ under Lorentz boosts in the z direction, which are used frequently in order to work in the center-of-mass frame of a collision. In addition, the number of particles produced in between η and $\eta + \Delta\eta$ is approximately constant as a function of η.

2.2.2 Magnet

The CMS magnet surrounds the inner three parts of the detector. Inside the magnet, it produces an almost uniform magnetic field of 3.8 T, parallel to the beam pipe of the LHC. All particles that have a magnetic moment—electrons, muons, pions, kaons, protons, and neutrons are the ones that live long enough to be appreciably affected—are deflected in the magnetic field, and the curvature of the trajectory is proportional to the particle's momentum. A stronger magnetic field also produces sharper curvature, giving a more precise momentum measurement. As mentioned above, the magnetic field strength was one of the motivations for the design choices in constructing the CMS detector.

The magnetic field is produced by a superconducting solenoid, 12.9 m long and 5.9 m in diameter. It carries a current of 19.5 kA. The iron return yoke of the magnet ensures that the return flux of the magnetic field goes through the muon chambers, so that muon tracks curve and their measurements carry momentum information to complement the information from the tracker.

2.2.3 Parts of the CMS Detector

2.2.3.1 Silicon Tracker

The silicon tracker is the innermost part of the detector and provides precise position and momentum measurements for all kinds of charged particles. As a charged particle travels through the tracker volume, it passes through the silicon sensors and excites some of the electrons in the silicon. The detectors collect that charge and provide micron-level resolution of the position of the hit. By matching hits, CMS reconstructs a track and determines the trajectory of the particle.

In addition to a curvature measurement that determines the momentum, the tracker also provides *vertexing* to determine where particles originate. Because each bunch crossing involves an average of around 38 collisions, it is important to determine which particles come from the collision of interest (the primary vertex) and which come from other collisions (pileup). Additionally, certain particles, like b quarks and τ leptons, live long enough to travel a short distance before decaying, producing a secondary vertex. By tracing the tracks back to their origin, we can determine each track's point of origin and associate it to the correct vertex.

The tracker is made of 17,004 silicon modules, rectangles measuring a few centimeters on a side. It is comprised of three several shells, each of which takes the form of a barrel and two endcaps in order to cover a large solid angle and capture as many of the particles produced in collisions as possible. The modules of the innermost shell, the barrel pixel (BPIX) and two forward pixel (FPIX) endcaps, which receive the most hits and require the highest precision, are contain pixels of 100 µm by 150 µm. A voltage is applied across the module, so that when a particle passes through a pixel module and creates electron-hole pairs in the silicon atoms, the charges move to the front of the module and are collected by a readout chip. Although the charge collection is done by individual pixels, the silicon module is made of one connected piece, and the charge deposited near one pixel is collected not only in that pixel but also in its neighbors. The readout chip measures the distribution of charge across pixels, and from this shape CMS can determine the position of the hit to a precision of several microns, more than an order of magnitude smaller than the size of the pixels themselves.

The middle shell is made of the Tracker Inner Barrel (TIB) and Disk (TID), and the outer shell consists of the Tracker Outer Barrel (TOB) and End Cap (TEC). Because these layers receive fewer hits per unit area than the innermost shell, the charge is collected by strips instead of pixels. While the width of each strip is around 100 µm like the pixels, the length is as long as the module, several cm. For this reason, the strip tracker provides only a one-dimensional measurement of the hit position within the module. Some of the strip modules are constructed as stereo modules, with two layers rotated by 100 µrad, or about 6°, with respect to each other. The combination of the two measurements gives some additional information that provides a less precise two-dimensional measurement.

The tracker measures the position of hits within a module, while the quantity of interest is actually the position of the hits in 3D space. While the transformation is easy to make, it introduces an additional possible source of error—our knowledge on the hit's position in space is limited by our knowledge of the module's position in space. The procedure to determine the module positions is discussed in detail in Chap. 3.

The tracker is sensitive to all charged particles, including electrons, muons, and several hadrons. It cannot measure the energy and momentum of neutral particles, including, most notably, photons and neutrinos.

2.2.3.2 Electromagnetic Calorimeter

The electromagnetic calorimeter, or ECAL, measures the energy of electrons and photons. In the case of elections, information from ECAL complements the momentum measurement of the tracker; for photons, ECAL provides the *only* measurement of their energy and momentum. The presence or absence of a track in the tracker also allows CMS to distinguish between electrons and photons.

ECAL's is constructed from 61,200 lead tungstate ($PbWO_4$) crystal scintillators in the barrel region and 7324 more in the endcap. $PbWO_4$ is a dense material with a radiation length of about 8.9 mm, but is also transparent. When an electron or positron passes through these crystals, it recoils off nuclei and produces *bremsstrahlung*, braking radiation. Similarly, in the presence of the heavy nuclei, high energy photons can convert into an electron-positron pair. The resulting cascade is known as an electromagnetic shower.

The low energy photons produced by the shower continue to the end of ECAL, where they are captured and measured. To amplify the signal and obtain a better measurement, photomultipliers in the form of avalanche photodiodes in the barrel region or vacuum phototriodes in the endcap region are used.

An electron or photon's energy decreases, on average, by $1/e$ while traveling a distance in the material equal to its radiation length. Because the width of ECAL is around 25 times the radiation length, electrons and photons deposit virtually all of their energy in ECAL and do not affect the measurements in the rest of the detector. Muons and even the lightest hadrons are significantly heavier than electrons and do not lose a significant amount of energy to bremsstrahlung. They continue to the outer parts of the detector. Neutrinos, as before, are unaffected.

2.2.3.3 Hadronic Calorimeter

The next subdetector, the hadronic calorimeter or HCAL, measures the energy of hadrons. As for electrons, the measurements from charged hadrons can also be matched to tracks in the tracker, while neutral hadrons, such as neutrons, only leave energy deposits in HCAL.

Unlike ECAL, HCAL is designed as a sampling calorimeter: not all of the energy is actually measured. Instead, it is formed from alternating absorber and scintillator layers. The absorber layers are made of brass, with a nuclear interaction length of about 16 cm. On this length scale, hadrons that pass through HCAL interact with the nuclei, lose their energy, and produce more, lower energy hadrons. This phenomenon is similar to the electromagnetic shower in ECAL, but involves interactions between the hadrons and the nuclei and proceeds through the strong force, with pions and other mesons taking the place of photons. The scintillator layers measure the energies of the hadronic particles that pass through them. By measuring this captured energy, HCAL can determine the energy of the original particle.

Like the other parts of the detector, HCAL is divided into barrel and endcap regions. In addition, there is an outer region outside the magnet, placed there to capture any particles that were missed by the barrel, and a forward region, designed to capture radiation that travels almost parallel to the beamline. The width of HCAL in the barrel region is around 10 times the nuclear interaction length, so it captures almost all of the energy of hadronic particles. The only particles left are muons and neutrinos.

2.2.3.4 Muon System

The muon system is designed to give precise measurements of muons. As the only charged particles not absorbed by ECAL and HCAL, muons are typically the only particles that leave a track in the muon system. In the barrel region, drift tube chambers (DTs) are used to detect muons, while in the endcap, cathode strip chambers (CSCs) are used instead. In both the barrel and endcap regions, there are also resistive plate chambers (RPCs). All three types of chambers are filled with gas, and the gas atoms are ionized by muons that pass through. In the DTs, the electrons drift to wires. In the CSCs, both the electrons and ions are collected by arrays of cathode and anode wires. In the RPCs, the electrons are collected by strips. The RPCs are especially precise at determining the time when muons arrive, which is necessary to associate the muon with a particular event, while the DTs and CSCs have better spatial resolution.

2.2.3.5 Neutrinos

Neutrinos are not detected by any part of the CMS detector and escape into space. To measure neutrinos or hypothetical BSM particles that barely interact with normal matter, we use conservation of momentum. Each collision involves protons moving in the z direction, with no momentum in the x or y directions. Therefore, the sum of the products' transverse momentum $\vec{p}_T$ must be zero as well. Any deviation is known as missing transverse energy, or MET, and is a sign of neutrinos or other undetected particles. This is one reason why capturing all of the other particles is so important: any missed particle results in an incorrect MET measurement.

2.2.4 Trigger

The LHC provides over a billion collisions per second, and most of those collisions produce nothing interesting. It is impossible to store the data from all of these collisions. Therefore, a solution must be found to distinguish between interesting and useless events, and this must happen fast enough so that the measurements made by the detector can be saved or dropped.

To accomplish this, a two-level triggering system is used. First, the fast level 1 (L1) trigger, using imprecise, raw measurements, determines whether to keep or drop the event. This is all done using custom hardware, and reduces the rate to around 100,000 events per second. Second, events that pass the L1 trigger are given to the high level trigger (HLT), which runs on software and has access to more information about the event. Around 100 events per second pass the second trigger. Events passing both triggers are saved and can be used in analyses.

2.2.5 Particle Identification and Reconstruction

To assemble all of the information from the subdetectors into a full picture of a collision event, the particle flow algorithm [6] is used. As mentioned above, each event involves an average of 37–38 collisions, which can all produce particles in overlapping regions of the detector. A method is needed to sort the particles and match information between different parts of the detector. Figure 2.4 summarizes how each type of particle interacts with the various parts of the CMS detector.

The particle flow algorithm first looks for muons, which are the cleanest signal, and matches tracks from the tracker to those from the muon chambers. Those tracks are then removed from consideration, and then the algorithm looks at electrons, matching energy deposits in ECAL with tracks in the tracker. The remaining energy

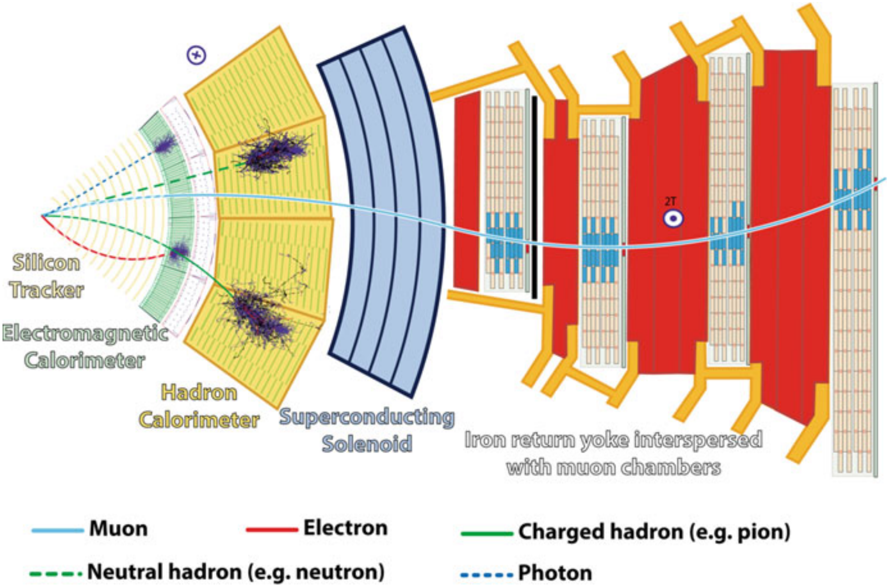

Fig. 2.4 A cross sectional view of the CMS detector, showing where each type of particle leaves its tracks or deposits its energy. This picture is from [5]

deposits in ECAL are photons. The algorithm then reconstructs hadronic jets, using the tracker and HCAL for hadronic particles and ECAL for photons produced by the jet.

Vertexing determines which particles are produced in which collision, as well as which particles are produced from secondary decays of long-lived particles. In addition, when an electron, muon, or photon is produced from the decay of a hadron in a jet, the close proximity between the particle and the jet can be used to determine that, include that particle's momentum in jet calculations, and exclude it from independent consideration.

Jets matching certain criteria, such as a secondary vertex matching the lifetime of B mesons, are tagged as b-jets, which are likely to have come from bottom quarks. Similar considerations are used to tag jets as being produced from τ lepton decays.

The events originally provided by the detector are saved in "raw" format. From there, they are processed into more useful data formats that contain electrons, muons, photons, jets, and MET, which can be used directly in analysis.

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