Basic Introduction to Detectors of the Large Hadron Collider

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Abstract: Particle physics is intended to explore the microscopic world, to be more specific, to understand the physical laws of particles. So far, the Standard Model (SM) is the best theory we have to explain particle properties and their behaviors. Such great success attributes to the data acquired from experiments in particle physics. These experiments not only provide evidence about the correctness of the SM but also reveal the limitations and what may be beyond the SM. Since microscopic phenomena cannot be observed by human eyes, it is necessary to use special instruments to do these experiments, and one of them is the Large Hadron Collider (LHC). This review shall introduce the basic information of the LHC and focus on the basic structure and principles of the detectors used in two experiment projects of the LHC.

1. Introduction

The LHC is the most important and renowned experiment structure in the field of particle physics. The primary goal of the LHC is to find the Higgs bosons and the potential new physics signatures in the TeV energy range [1-2].

It allows us to observe high-energy particle events by accelerating particle beams to very high velocities and having them collide with each other. And then, we can learn the inner structures and properties of particles with the data from observation. The LHC has helped us achieve many scientific goals, and the most famous of them is finding the evidence of Higgs bosons which explains why particles have mass. Besides the discovery of Higgs bosons, the LHC also helped us in studying dark matter, neutrino, and so on [3-5].

The first part briefly introduces the process of particle detection in the LHC. The second part focuses on detectors used in Compact Muon Solenoid (CMS) and Toroidal ApparatuS (ATLAS). The third part tries to show the basic principles of scintillator detectors and semiconductor detectors. And the final part shall briefly introduce applications coming from the LHC.

2. Process of particles detection

Although built in the tunnel left by the large e+e− collider (LEP), the LHC can reach much higher energy and luminosity. It has been designed with four cross-sections where particle beams collide. Each section is for one experiment: CMS and ATLAS are for proton-proton collisions with high luminosity, the Large Hadron Collider beauty (LHCb) is designed for B-meson experiments requiring proton-proton collisions with medium luminosity, and the A Large Ion Collider Experiment (ALICE) is dedicated to heavy-ion collisions requiring low luminosity for the operation with proton beams [6].

The whole process of particles can be divided into five steps (Figure 1). Firstly, the protons or ions are created and then injected into the tunnel to be further accelerated. To fill the LHC with protons or ions, a range of pre-accelerators is required, which consists of a source and linear accelerator as well as three assisting rings to inject particles into the LHC. Secondly, the high-energy beams containing trillions of particles will be accelerated by a magnetic field to high velocity. Then they collide and produce new particles, which can be described as physic events creating physic signals. Thirdly, to use electronic devices like computers to analyze these physical signals, it is necessary to convert them into electronic signals, which is done by the detectors. Then, the electronic signals have to be processed before being sent to computers so that potential errors can be minimized as much as possible. After the four steps above, we analyze data to find hints of particles and physics.

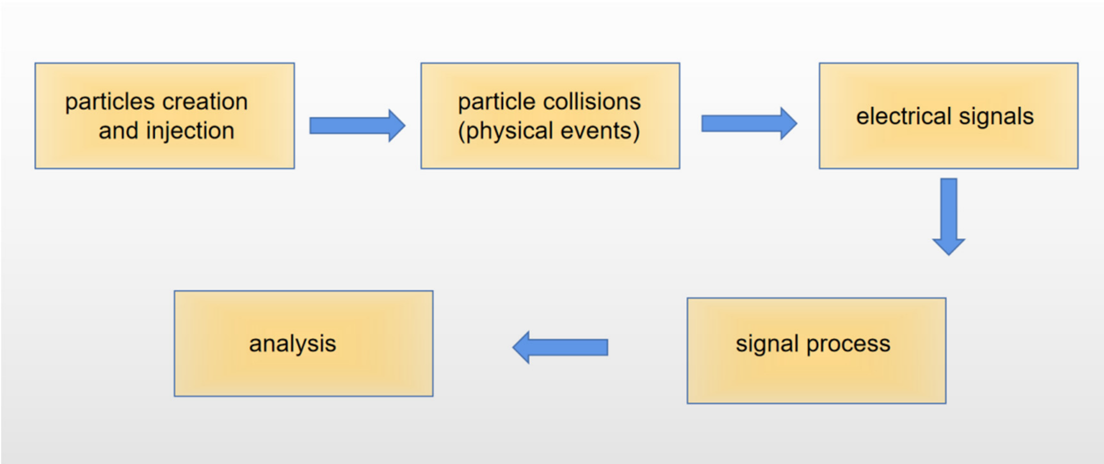

Figure 1. The steps for particle detection.

3. CMS and ATLAS

Both of them are designed for high-energy situations with many sub-detectors, and they share the same basic structure, but because of their stronger magnetic fields, CMS is capable of higher energy situations than ATLAS.

3.1. Basic structure of CMS

As shown in Figure 1, the CMS consists of an inner track system, a muon system, and a superconducting magnet. The role of the magnet is to create a homogeneous magnetic field to move particles so that we can collect trajectory information. A 4-T superconducting solenoid with 13 meters long and 6 meters inner diameter lies at the center of the CMS, providing a large bending power (12 Tm) before the muon bending angle is measured by the muon system.

The muon system is for distinguishing signatures of important processes, such as the decay of Higgs Bosons and muon final states, from the very high background rate due to the full luminosity in the LHC. It consists of many muon stations capable of reconstructing the momentum and charge of muons within the kinetic range of the LHC. Every muon station consists of several layers of drift tubes (DT) made of aluminum in the barrel region and cathode strip chambers in the end-cap region, complemented by resistive plate chambers [7].

The inner tracking system, including a silicon tracker, a pixel detector, and a transition radiation tracker, is closest to the collision location. It collects trajectory information of the particles moving in a homogeneous magnetic field, as well as the position of secondary vertices. Trajectory information tells us the momentum and magnetic moment of particles, which are basic properties of particles. To fulfill this task, it is designed to be capable of high granularity and fast response detection. There are three layers of silicon pixel detectors covering the inner region to improve the precision of the measurement [8].

The calorimeter is to collect the energy information of particles. The electromagnetic calorimeter is for charged leptons such as electrons, especially the decay of Higgs Bosons[9]. The hadron calorimeter is for particles involving strong force, searching for hadron jets and neutrinos or exotic particles causing obvious missing transverse energy [10], and a forward calorimeter is for luminosity measurement.

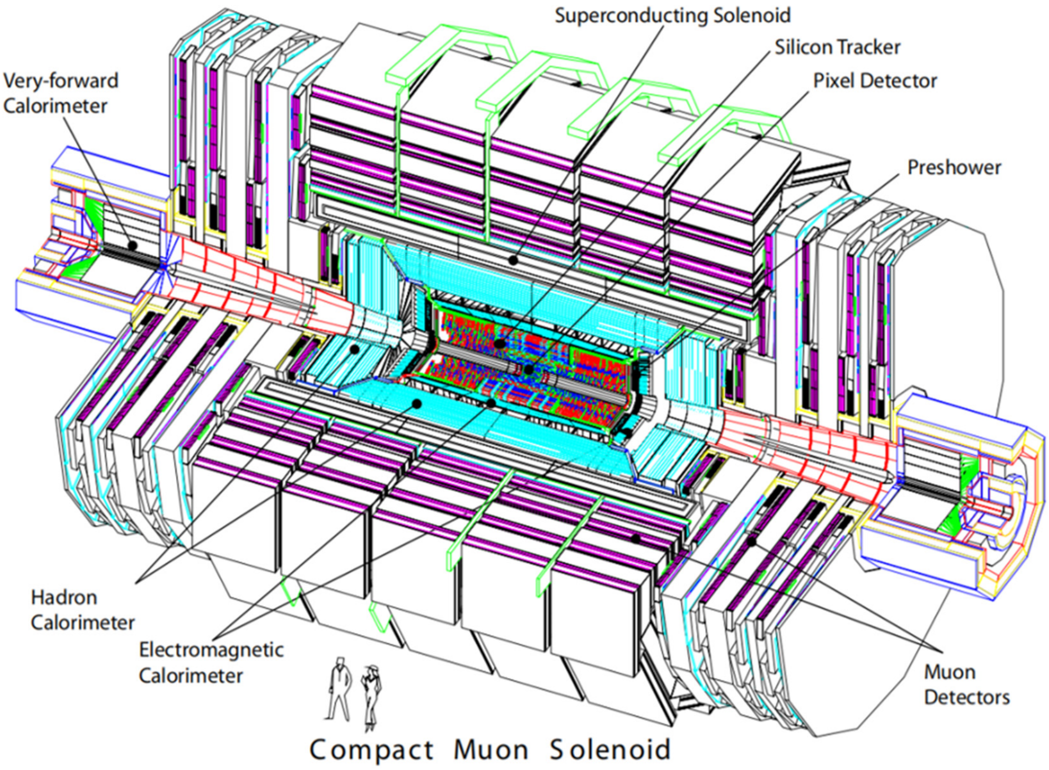

Figure 2. The structure of the CMS [7].

3.2 Basic structure of ATLAS

As we can see in Figure 3 below, there aren't many differences between the basic structure of CMS and ATLAS. ATLAS also contains an inner tracking system, muon system, and superconducting magnet.

The biggest difference between them is the solenoid. A thin superconducting solenoid formed by the magnet configuration covers the inner-detector cavity. And three large superconducting toroids (one barrel and two end-caps) are arranged with an eight-fold azimuthal symmetry around the calorimeters.

The center of ATLAS is immersed in a 2T solenoidal field. Many semiconductor pixels combine with strip detectors in the inner part of the tracking volume, aiming to recognize patterns, measure momentum and vertex, and identify electrons.

At the outer part, the muon spectrometer surrounds the calorimeter. The air-core toroid system, with a long barrel and two inserted end-cap magnets, generates strong bending power in a large volume within a light and open structure. Therefore, multiple-scattering effects are minimized, and three layers of high-tracking chambers with high precision provide excellent muon momentum resolution [11].

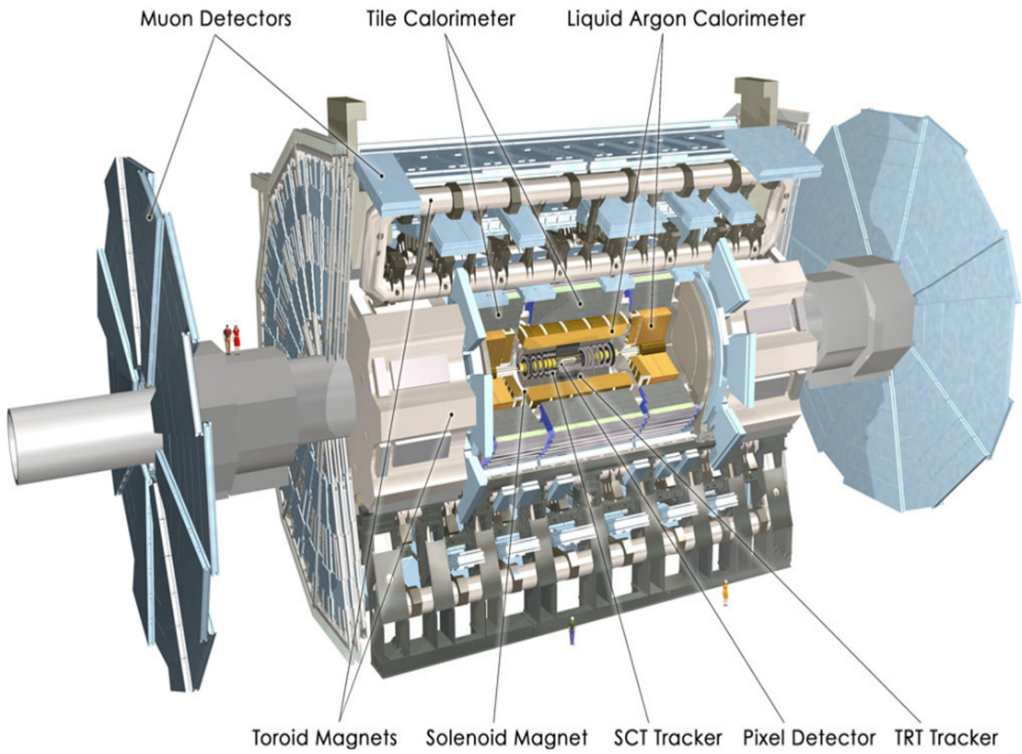

Figure 3. The structure of ATLAS [8].

4. Scintillator detector and semiconductor detector

There are various kinds of detectors in CMS and ATLAS, but in general, they can be divided into two categories: scintillator detectors and semiconductor detectors. Therefore, understanding the basic principles for these two kinds of detectors is very useful for further comprehension of the LHC.

4.1 Scintillator detector

The basic structure of the scintillator detector is shown in Figure 4, in which there are two important parts of it, the scintillator and the photomultiplier tube.

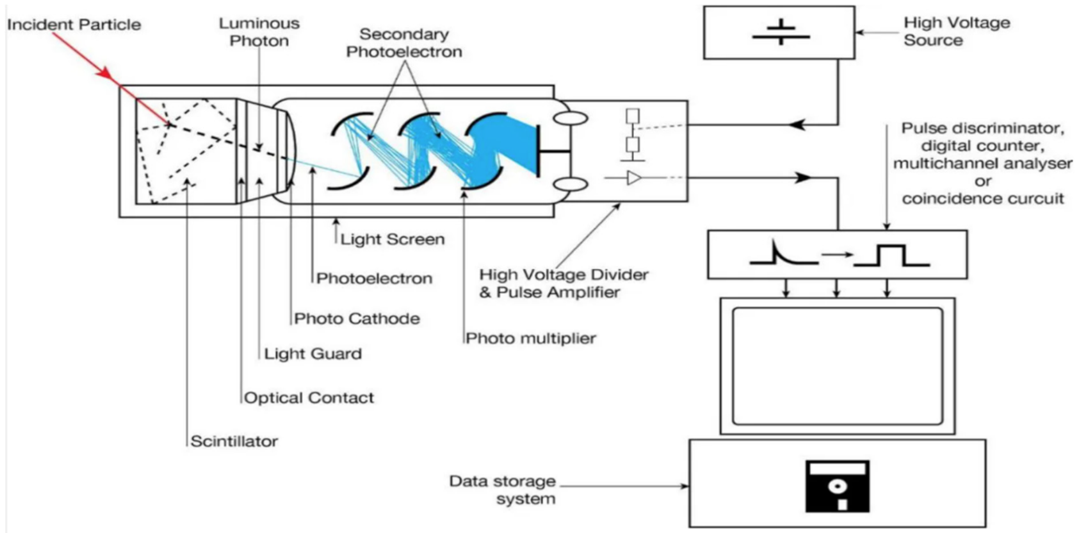

Figure 4. The structure of scintillator detector.

When the particles enter the scintillator, they lose their energy by interacting with the molecules of the scintillator, causing the molecules to be excited, which causes the scintillator to emit photoelectrons. Next, these photoelectrons enter the photomultiplier tube and hit the dynodes attached to the tube. The function of the dynodes is to amplify by emitting more secondary photoelectrons than the photoelectrons they absorb. Therefore, a weak electronic signal can be amplified into a stronger electronic signal which is easier to analyze for computers.

The calorimeter stems from the scintillator detector, so the principle of the scintillator detector is also the basic principle of the calorimeter.

4.2 Semiconductor detector

The basic structure of the semiconductor detector is shown in Figure 5 below. Before particles enter, the intrinsic region between the P electrode and N electrode is electrically neutral, and there are no electronic output signals. After particles enter the sensitive area, the particles lose energy, and the molecules of the intrinsic region are excited, which produces many electron-hole pairs. Driven by the electric field, the electrons move to the P electrode, and the holes move to the N electrode, making the intrinsic region not electrically neutral. Therefore, the voltage of the intrinsic region corresponds with the particles entering the intrinsic region, and the whole detector output signals are related to the energy information of particles.

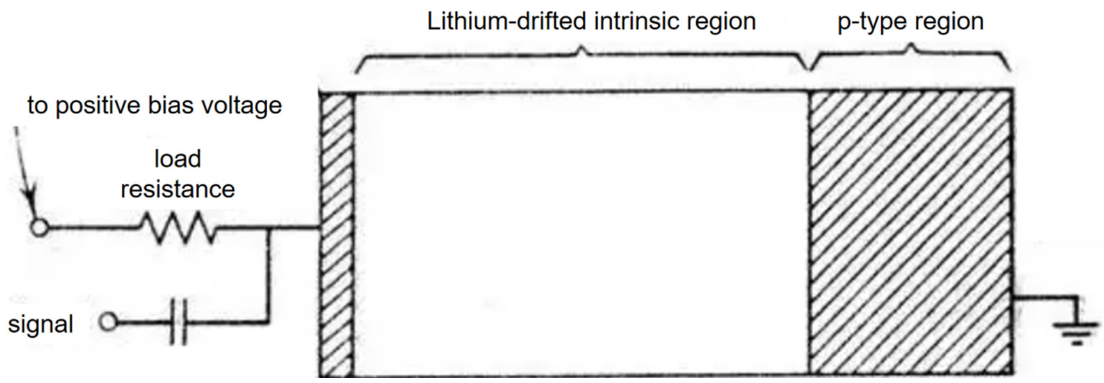

Figure 5. The structure of semiconductor detector.

Since detectors of the inner tracking system are semiconductor detectors, the principle of semiconductor detectors is also their basic principle.

5. Applications of the LHC

Like many other important scientific projects in human history, the LHC has promoted technology development in different fields. Because the high standard demands brought by the LHC bring many challenges, the experience of overcoming these challenges contributes to the further development of the relevant fields, such as big data processing. The particle beams at the LHC are comprised of proton bunches with a frequency of more than 40 MHz, and every collision has the potential to produce a large number of particles. Therefore, how to handle big data with high volume and complexity is a serious problem, and such a challenge has driven the development of data processing software [12].

Similar promotions also can be found in other fields. The problem of how to transfer big data becomes the foundation of the modern Internet, while the superconducting magnet boosts the development of the normal temperature superconducting materials.

6. Conclusion

While CMS is designed for high-energy situations and ATLAS is for low-energy situations, both of them follow similar structures and ideas, and so do the detectors they use. The paper reviews the basic structures of CMS and ATLAS, as well as the fundamental principles of scintillator detectors and semiconductor detectors. It helps us to realize the importance of detectors and to cultivate our further interest in particle physics.

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